Black Carbon from Biomass Burning in the Arctic

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MODIS-Terra image, May 7, 2003
Courtesy NASA Earth Observatory

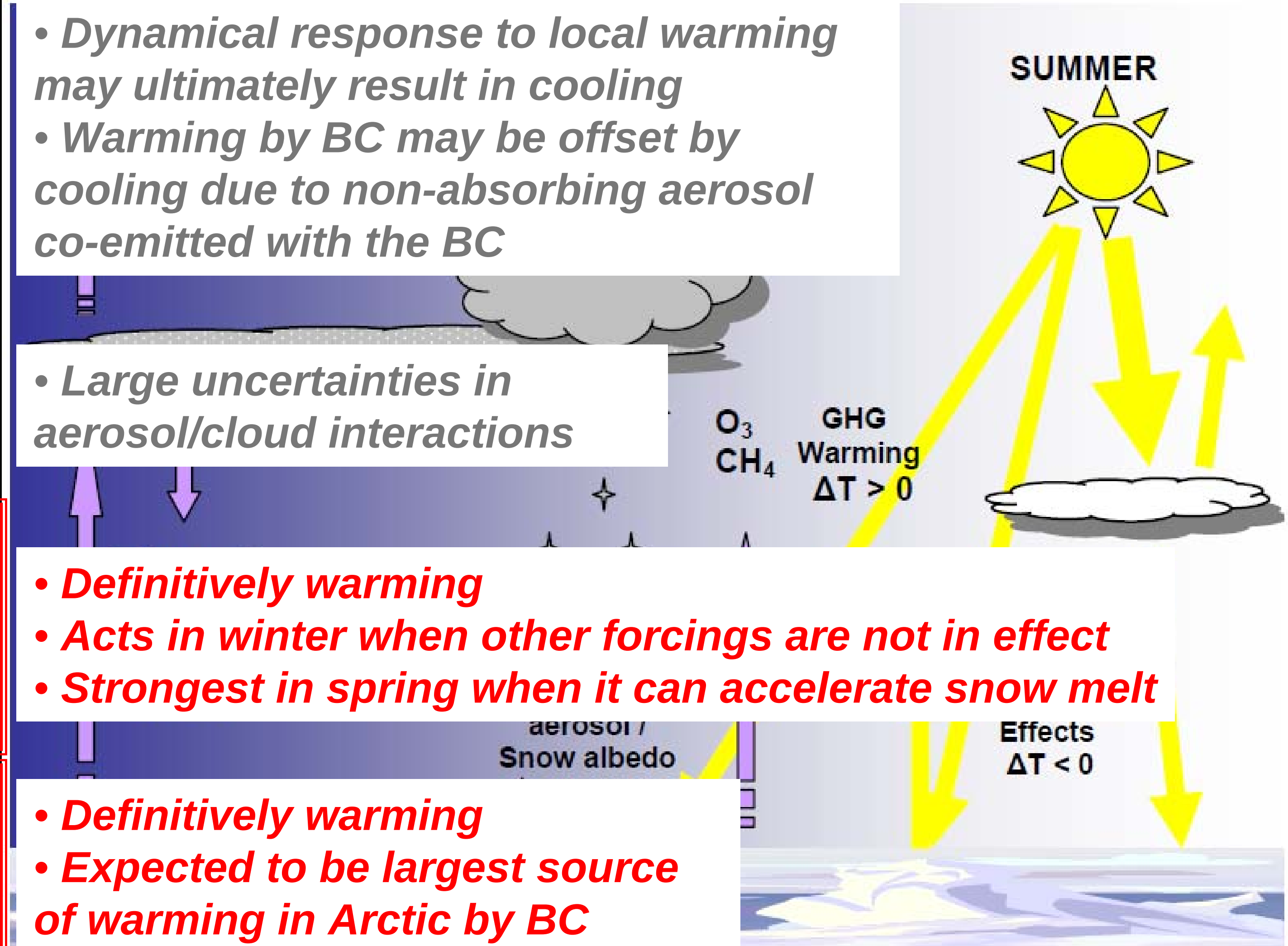
How does BC affect Arctic climate?

***DIRECT EFFECT:* Sunlight absorbed in the atmosphere by black carbon → warming?**

***INDIRECT EFFECT:* Increase in cloud cover → cooling**

***EMISSIVITY:* Increased infrared emission to surface → warming**

***SURFACE ALBEDO:* darkening of snow → warming**



- ***Dynamical response to local warming may ultimately result in cooling***
- ***Warming by BC may be offset by cooling due to non-absorbing aerosol co-emitted with the BC***

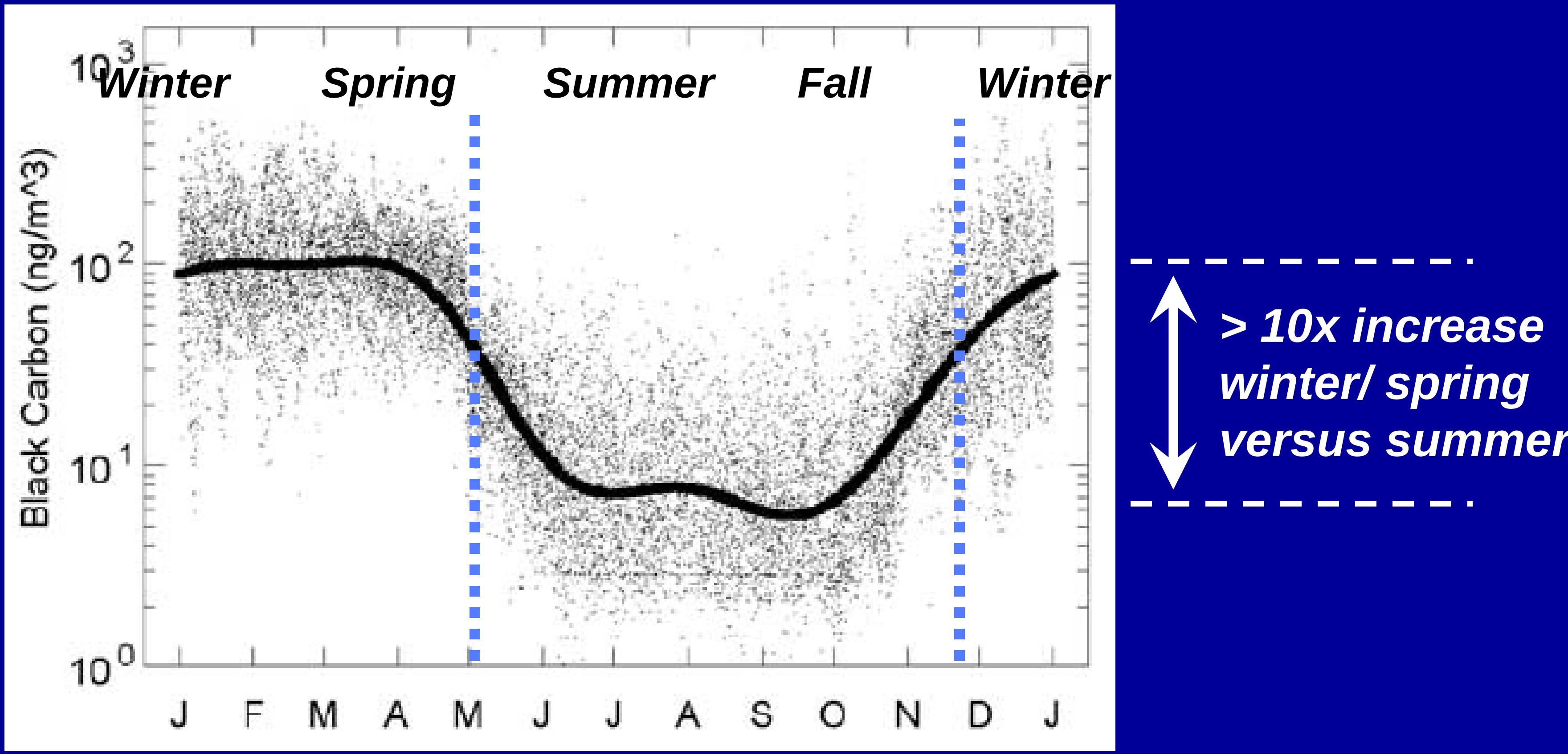
- ***Large uncertainties in aerosol/cloud interactions***

- ***Definitively warming***
- ***Acts in winter when other forcings are not in effect***
- ***Strongest in spring when it can accelerate snow melt***

- ***Definitively warming***
- ***Expected to be largest source of warming in Arctic by BC***

Quinn et al., *Atmos. Chem. Phys.*, 8, 1723, 2008

When does BC affect Arctic climate?



Average 1989-2002 black carbon concentrations
Alert, Canada 82°27’N, 62°31’W

Sharma et al., *J. Geophys. Res.*,109, D15203, 2004

Focus on sources of BC to Arctic:

- in ***winter*** and ***spring***, when concentrations are highest

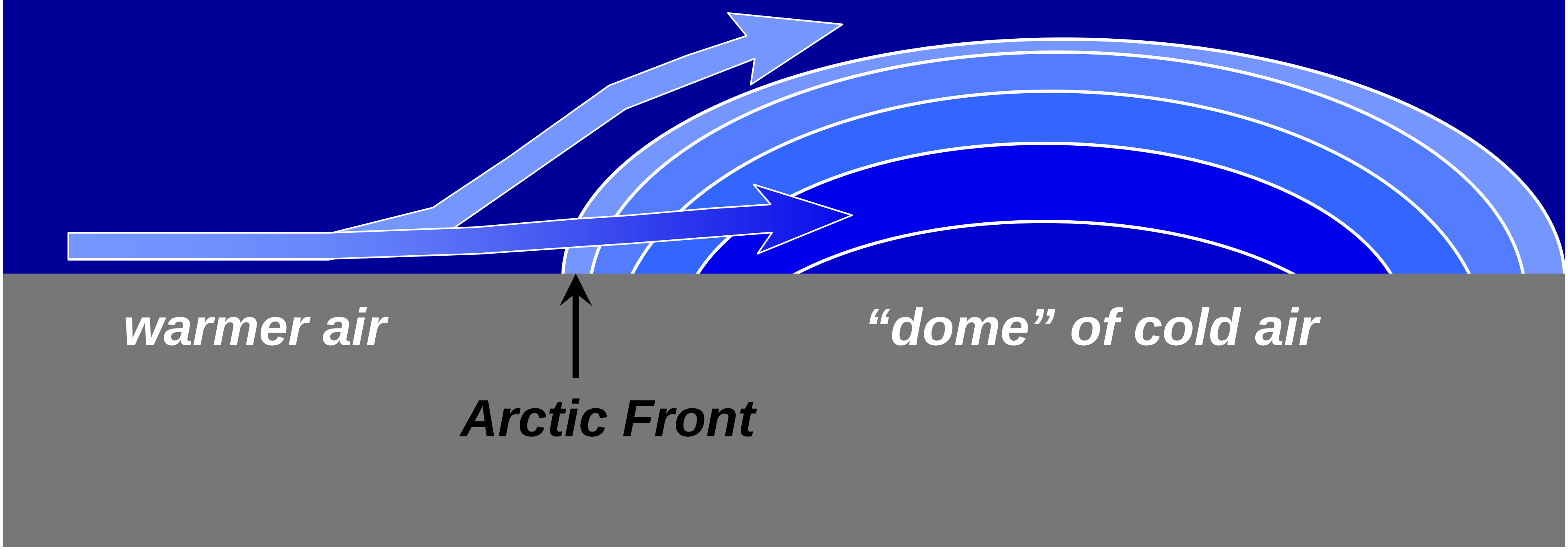
- to ***lower troposphere***, where BC can interact with clouds (<2km altitude) and be deposited on surface and darken snow

Concentrations of BC in the Arctic are a function of:

- <u>emissions</u> in source regions
    - fossil fuel burning → *anthropogenic*
    - biofuel burning → *anthropogenic*
    - forest and grassland fires → *natural & anthropogenic*
    - agricultural fires → *anthropogenic*
- <u>transport</u> (driven by winds)
- <u>losses</u> during transport
    - "wet" deposition to surface in rain and snow-fall
    - "dry" deposition to surface via settling

Transport of air into the Arctic

- “Dome” of cold air acts as a transport barrier into the Arctic
- Southern limit of this dome defines the Arctic front
- Air follows lines of constant potential temperature so for source regions south of the Arctic front, air that flows north is lifted over the dome unless the air is cooled in transit → i.e. by flowing over snow-covered surfaces.

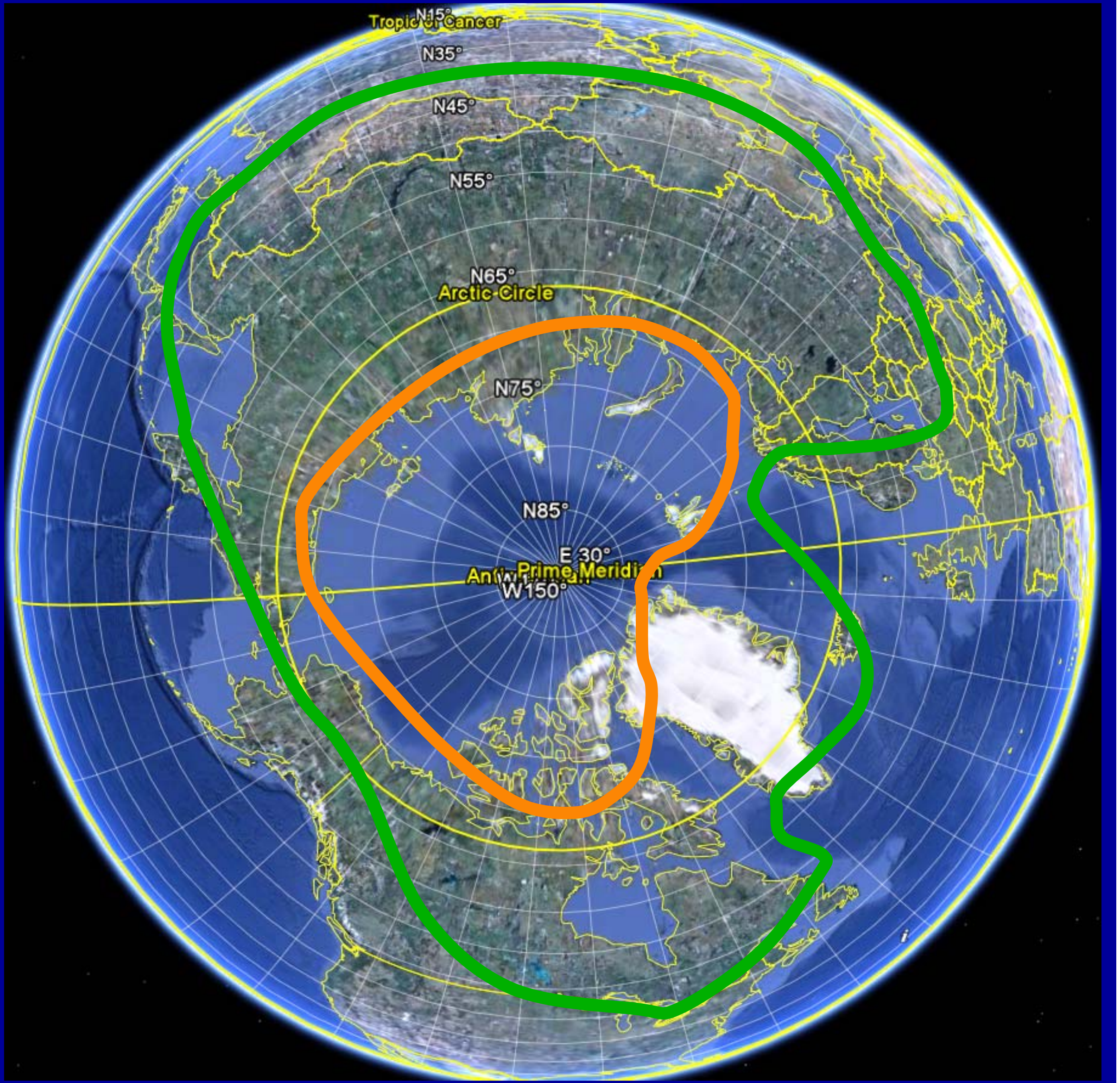


Arctic Front:

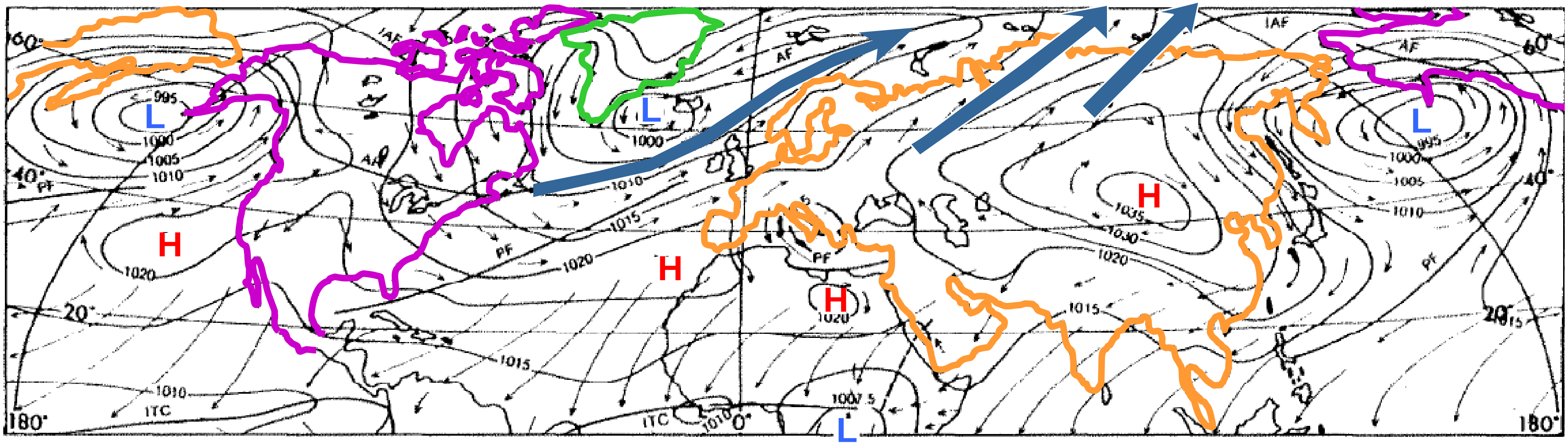
WINTER

SUMMER

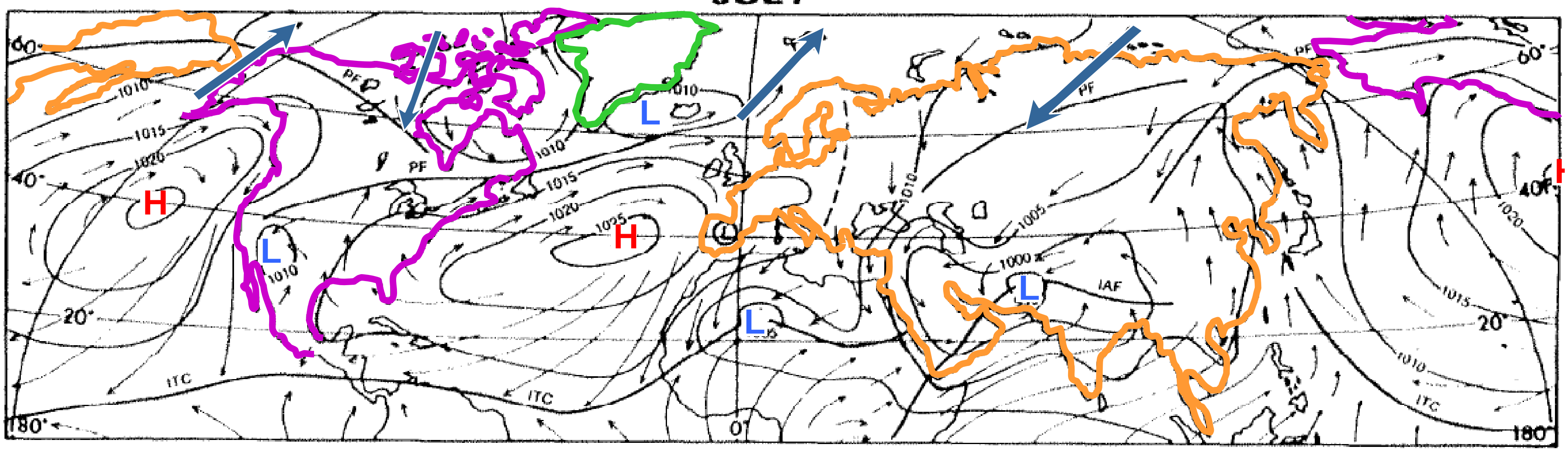
In winter, reaches as far south as 40°N in Eurasia, encompassing more populated areas



JANUARY



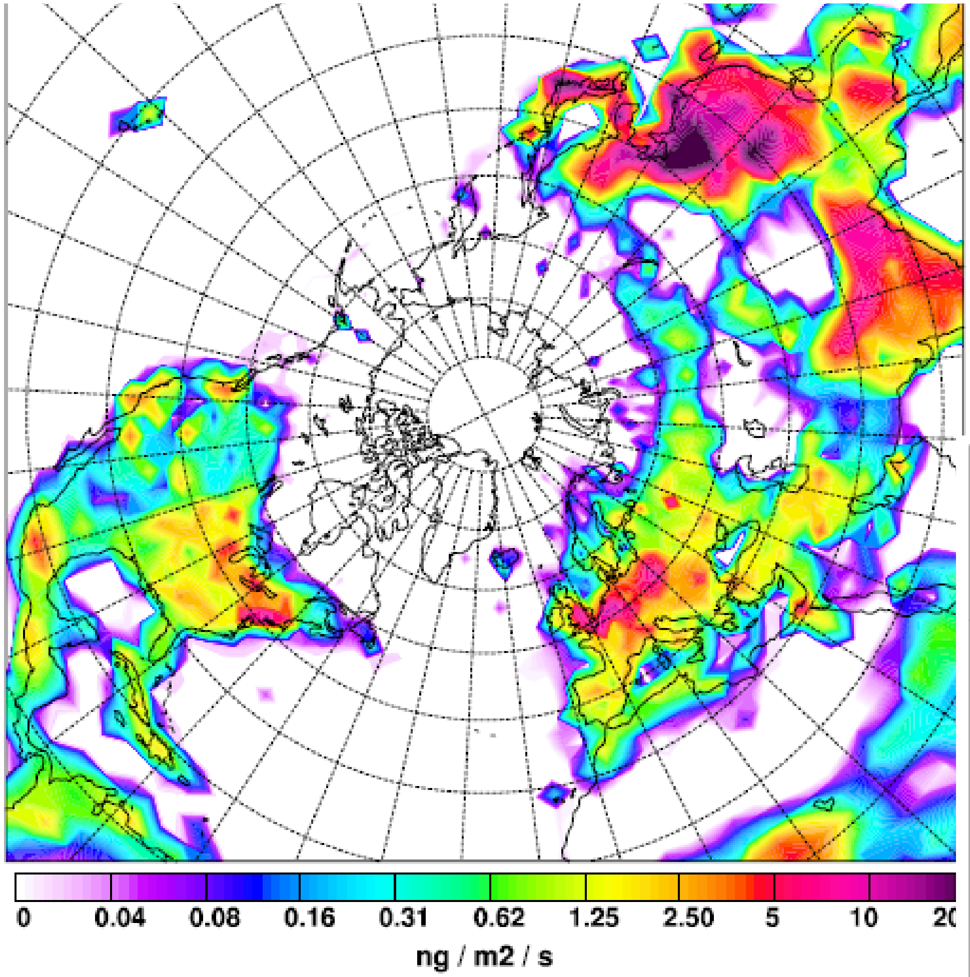
JULY



Barrie, *Atmos. Env.*, 20, 643, 1986.

Annual average black carbon emissions

(Note: does not include agricultural fires!)

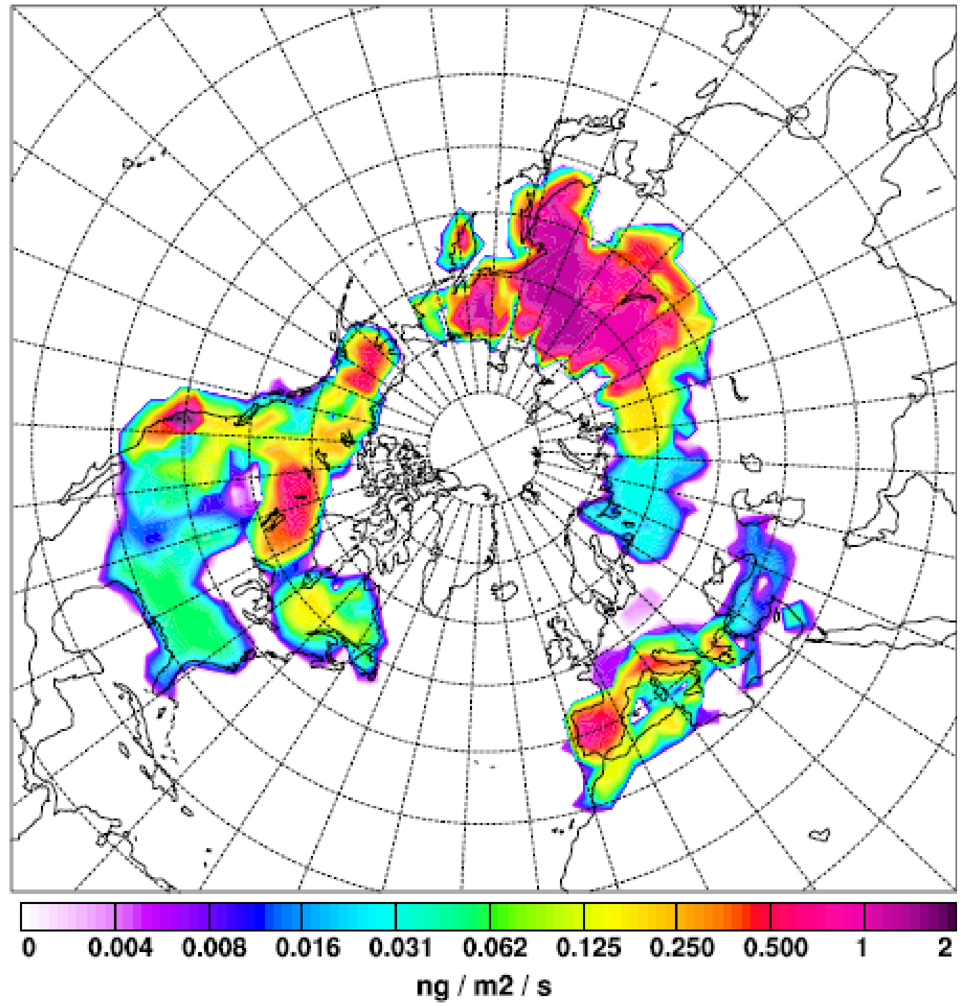


Fossil + bio-fuel

(from Bond et al., 2004)

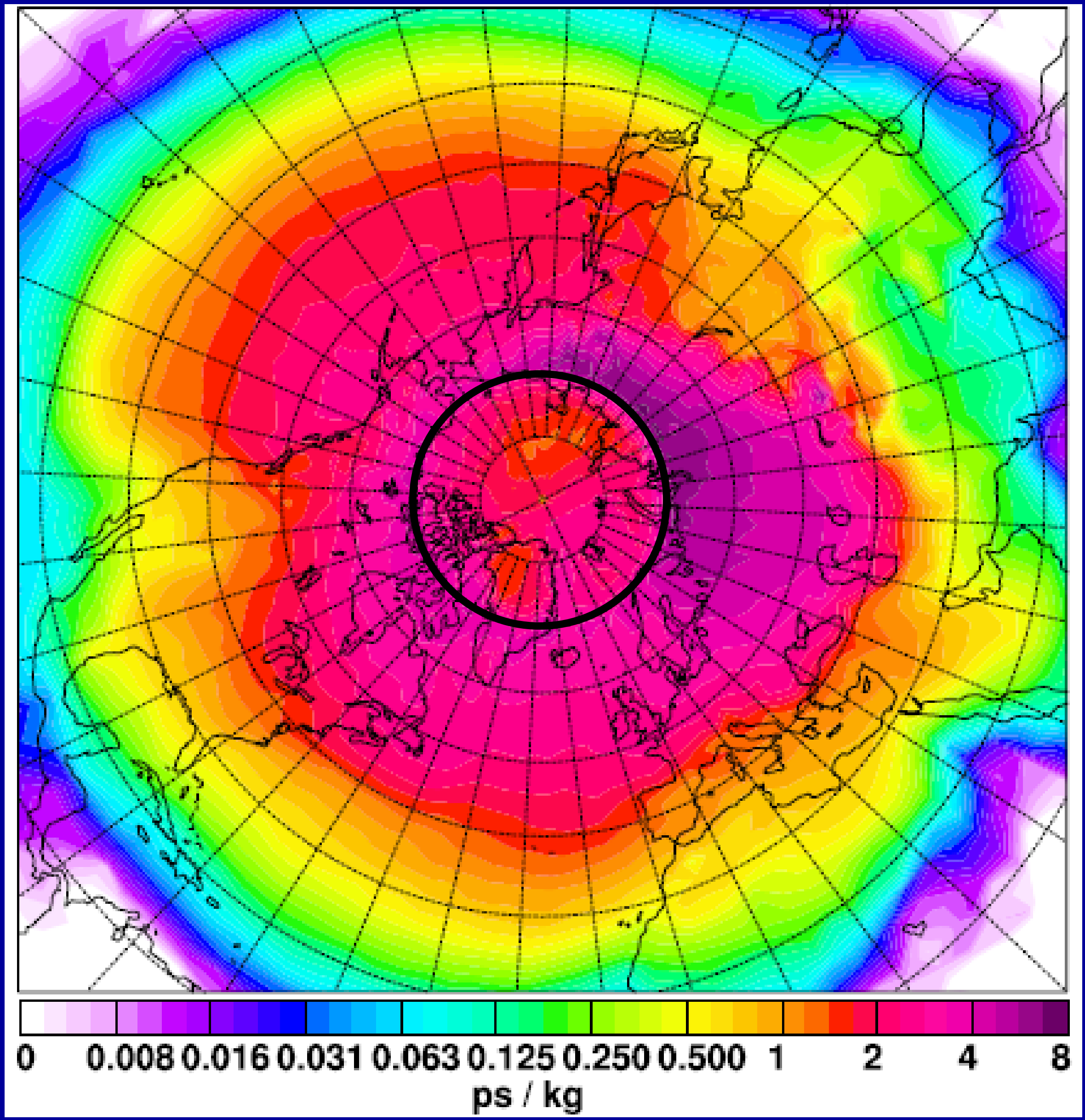
Boreal wildfires

(from Lavoué et al., 2000)



Stohl, *J. Geophys. Res.*, 111, D11306, 2006.

Result of emissions + transport:



Potential Source Contribution to Arctic (>70°N)

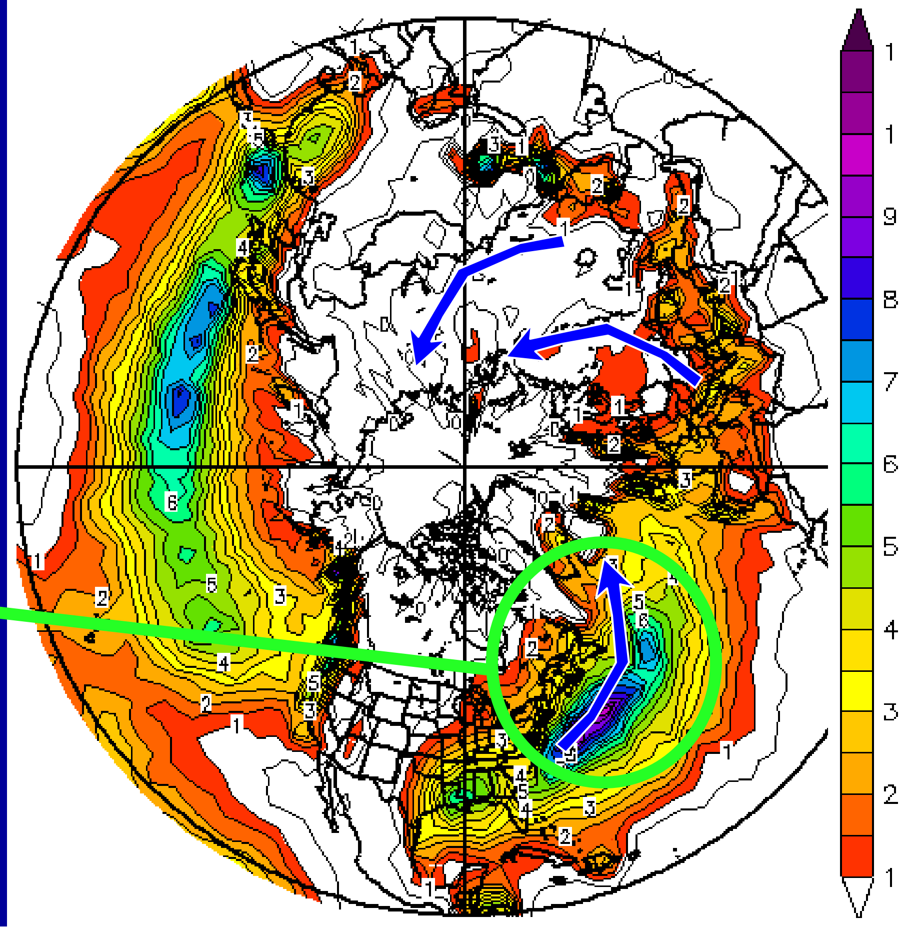
for 10 day integration

Stohl, *J. Geophys. Res.*, 111, D11306, 2006.

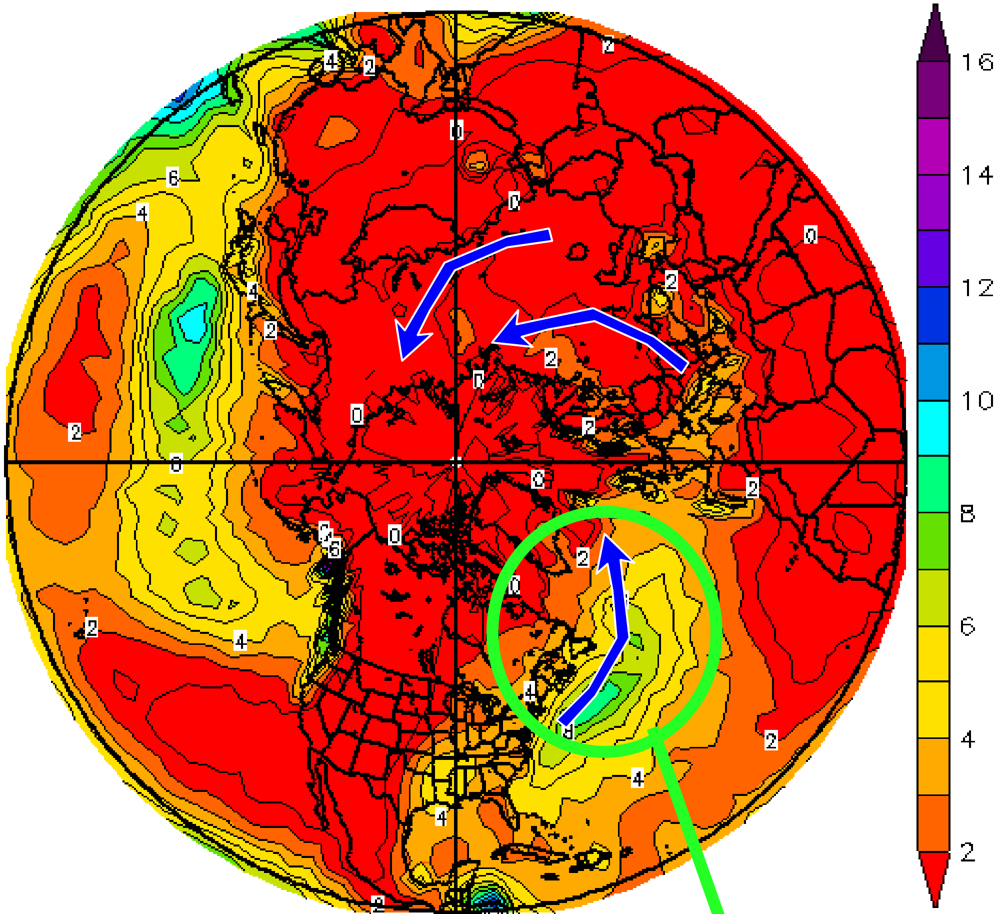
Losses during transport: 75-95% of loss is via wet deposition in precipitation

1979-1996 average precipitation

January-March



October-December



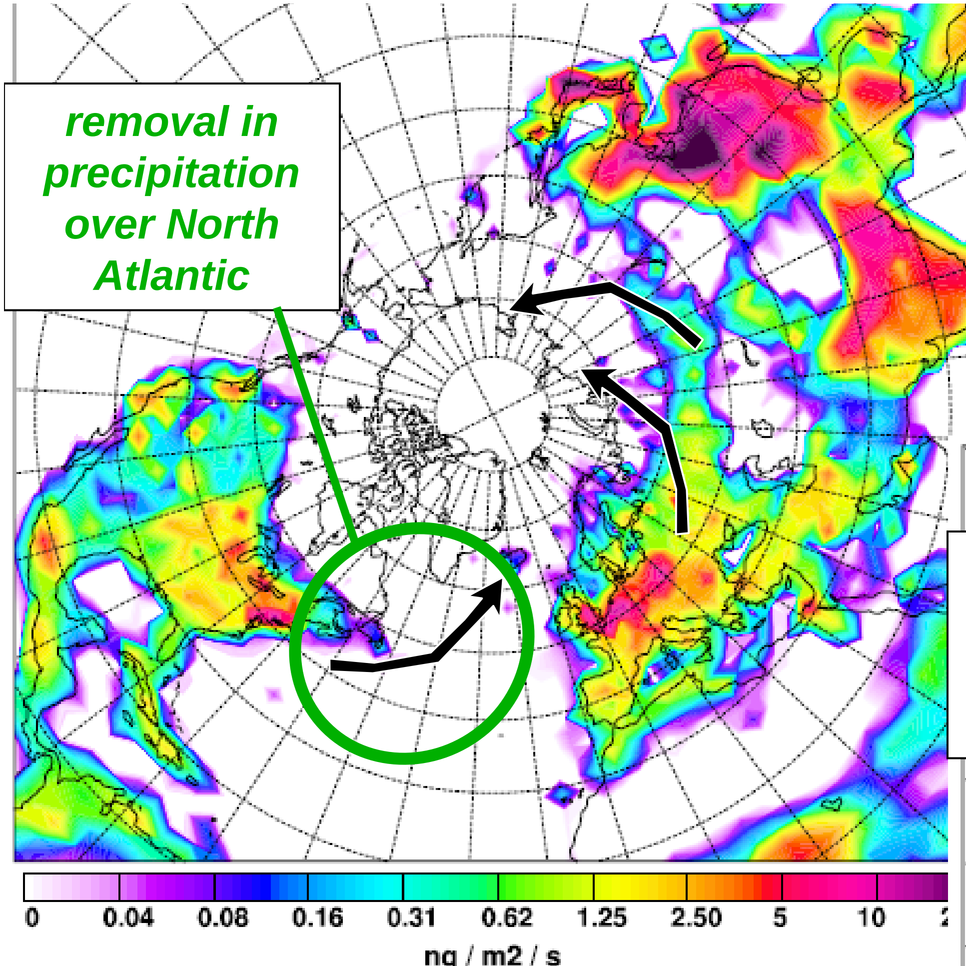
Wet deposition of aerosol over N. Atlantic

(lack of precipitation/wet deposition in Eurasian source regions)

NOAA-CIRES Climate Diagnosic Center

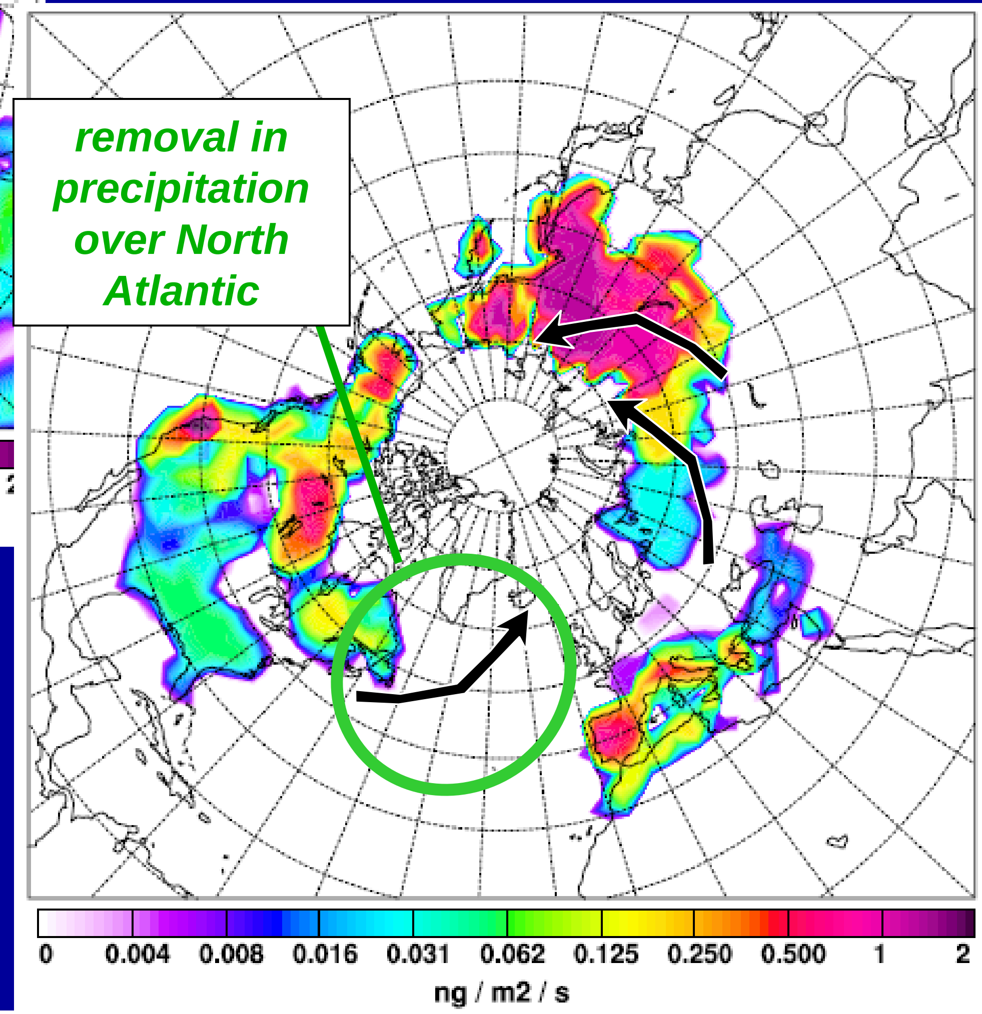
Annual average black carbon emissions

(Note: does not include agricultural fires!)



Fossil + bio-fuel

(from Bond et al., 2004)



Boreal wildfires

(from Lavoué et al., 2000)

Stohl, *J. Geophys. Res.*, 111, D11306, 2006.

Result of emissions + transport + losses (deposition) during transport:

"Nature and man have conspired to make northern Eurasian sources far more available to the Arctic than those in North America"

~ L. A. Barrie, *Atmos. Env*., 20, 643, 1986.

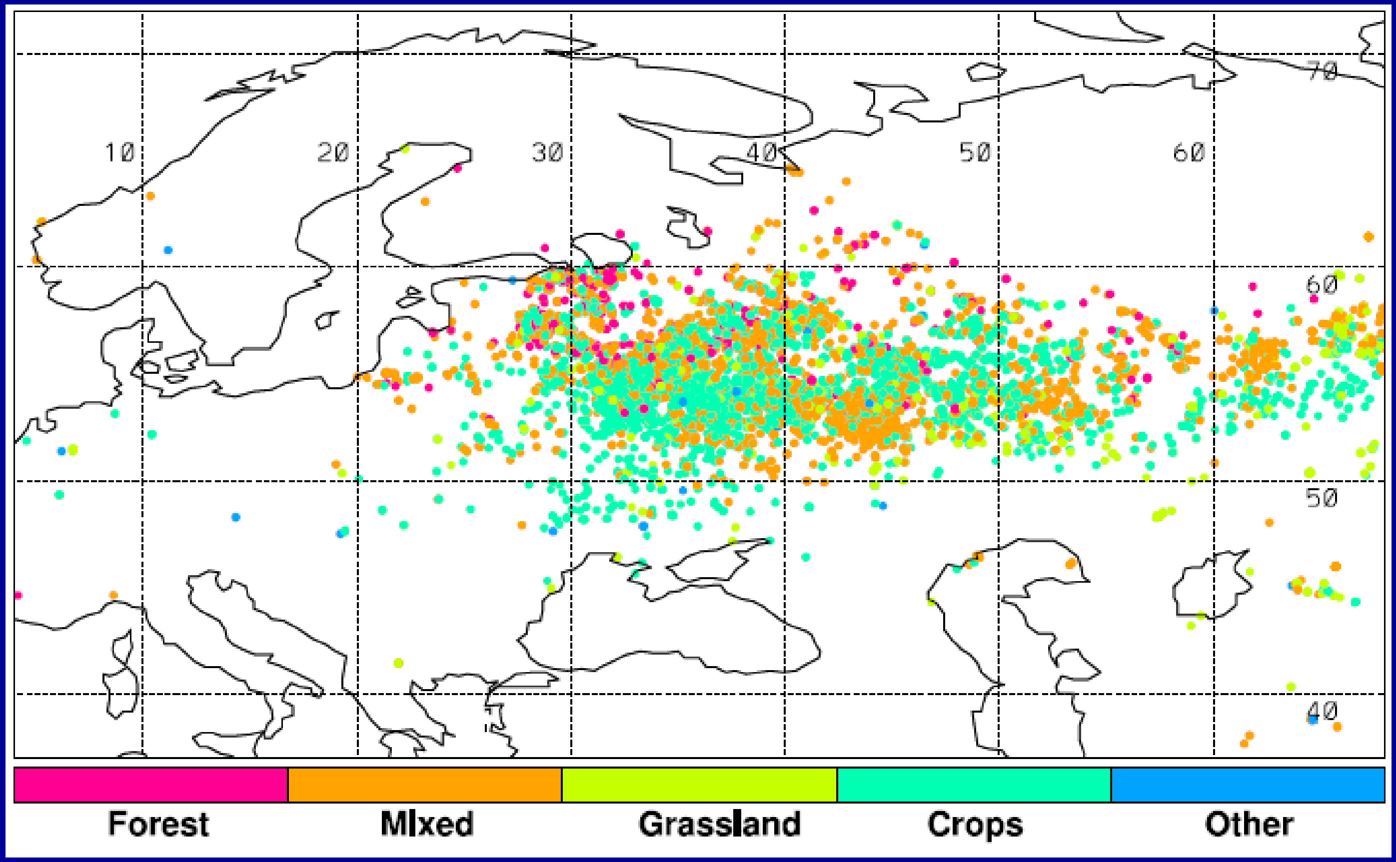
At least, this is what climate data + model simulations tell us…

how about measurements in the Arctic?

Early April- early May 2006 biomass burning

Stohl *et al., Atmos. Chem. Phys.*, 7, 511, 2007.

Late spring snow melt triggered intense field burning in April, to clear fields in western Russia, the Baltic countries, Belarus & the Ukraine.

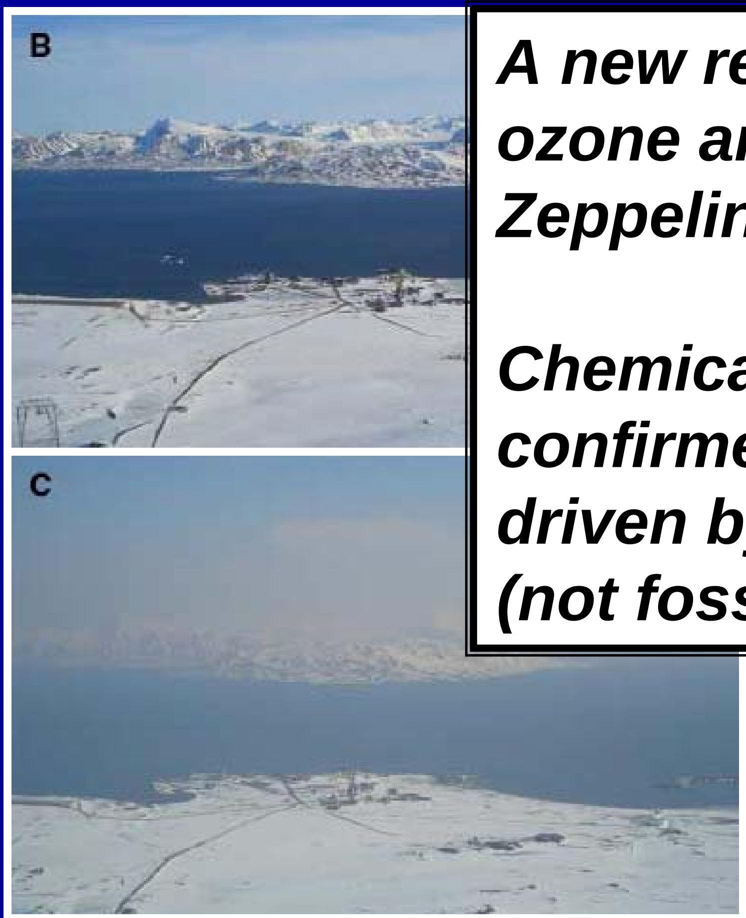


NASA MODIS fire counts 21 April – 5 May 2006

Early April- early May 2006 biomass burning

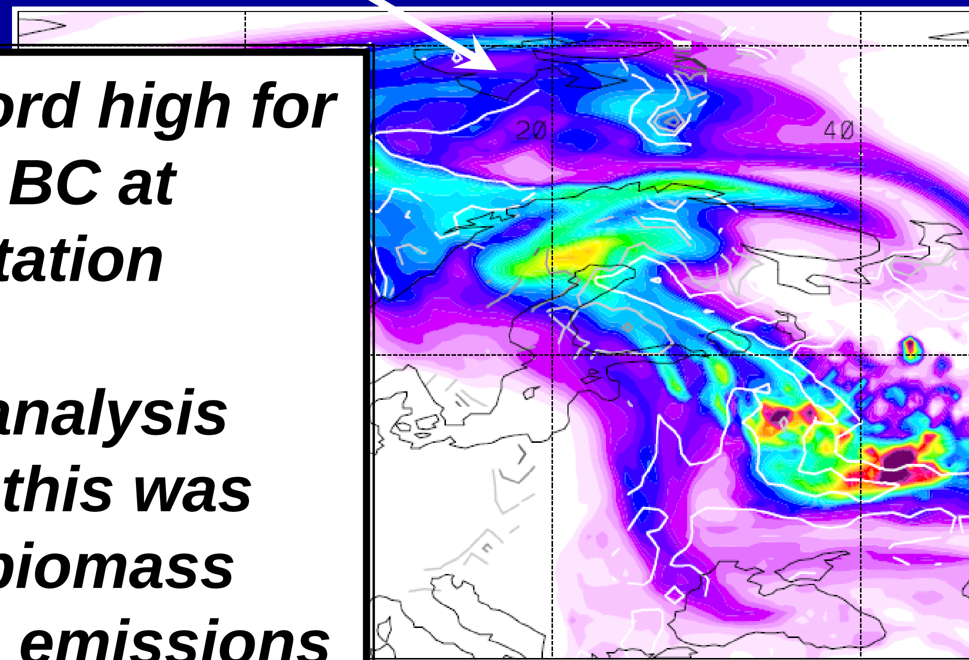
Stohl *et al., Atmos. Chem. Phys.*, 7, 511, 2007.

Meteorology allowed for efficient transport to Arctic, as measured at Zepplin station, Spitzbergen (78.9°N, 11.9°E)



A new record high for ozone and BC at Zeppelin station

Chemical analysis confirmed this was driven by biomass (not fossil) emissions

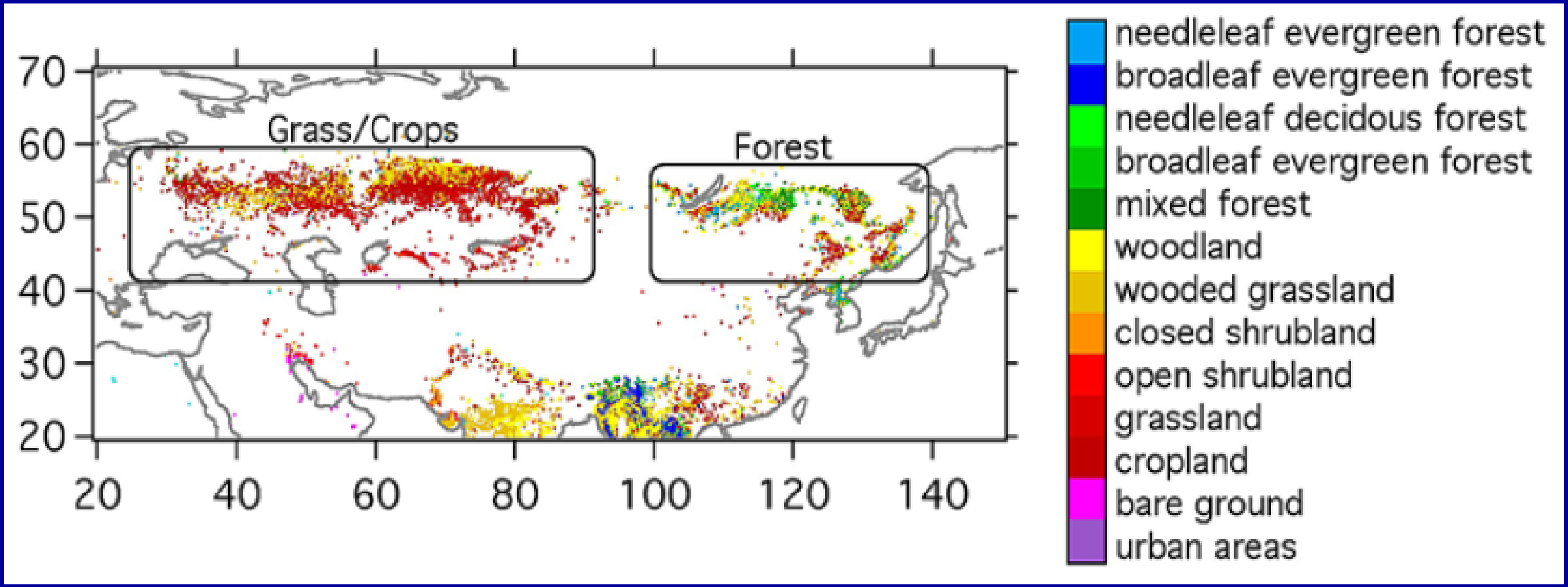


Satellite-derived CO and aerosol optical depth show transport of biomass emissions into Arctic

April, 2008: International Polar Year
Spring field campaign in N. American side of Arctic

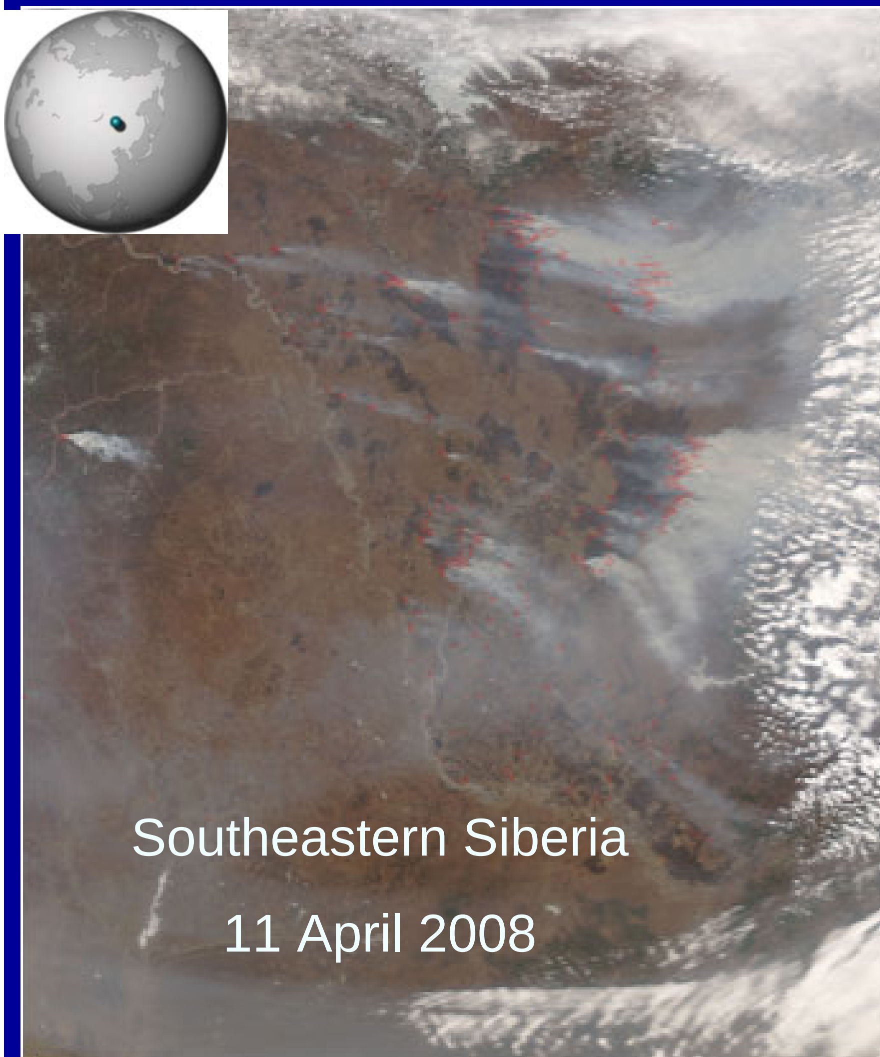
Warneke *et al., Atmos. Chem. Phys.*, 10, 5065, 2010.

- High concentration plumes measured aloft north of Alaska by NOAA WP-3 aircraft
- Chemical analysis and transport modeling traced these back to forest fires in southern Siberia-Lake Baikal and agricultural burning in Kazakhstan-southern Russia.



NASA MODIS fire counts 1-20 April 2008

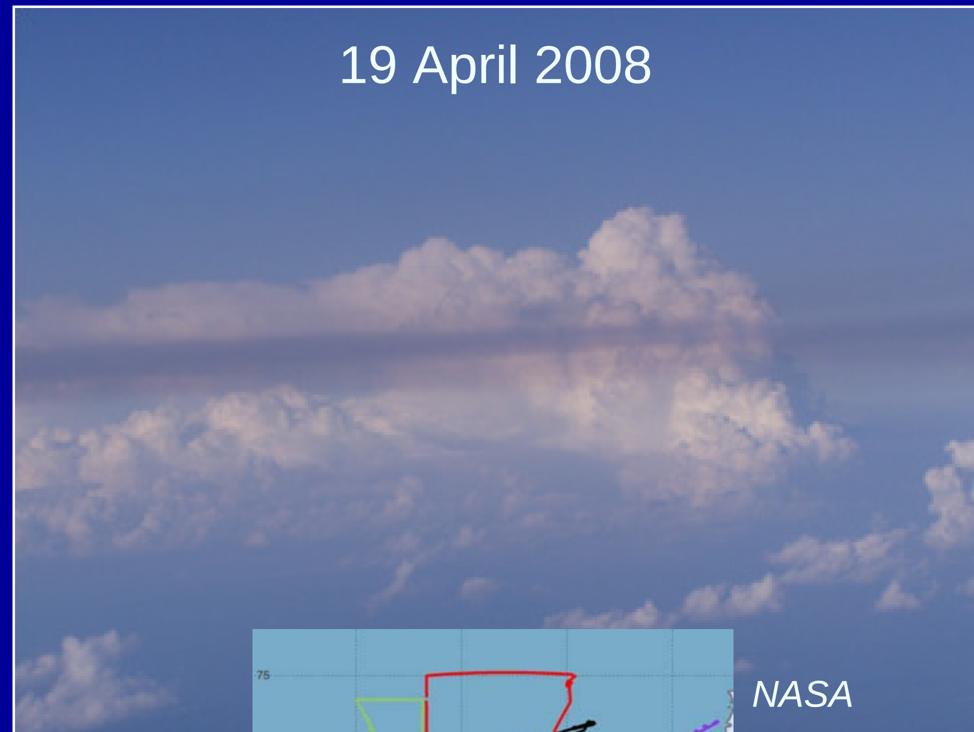
April, 2008: Plumes from Siberian Fires in the Arctic



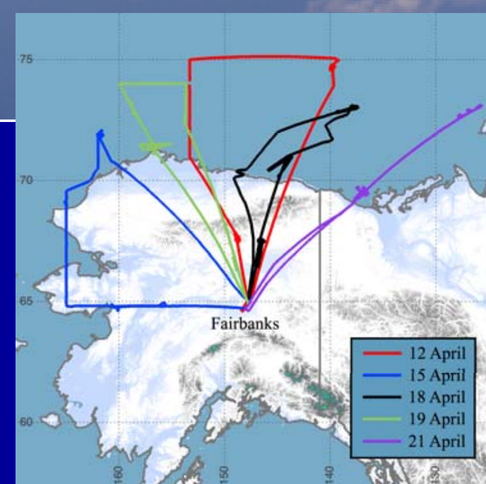
MODIS satellite image of fires & smoke

image courtesy of NASA/University of Maryland

Plumes observed from aircraft in Alaska

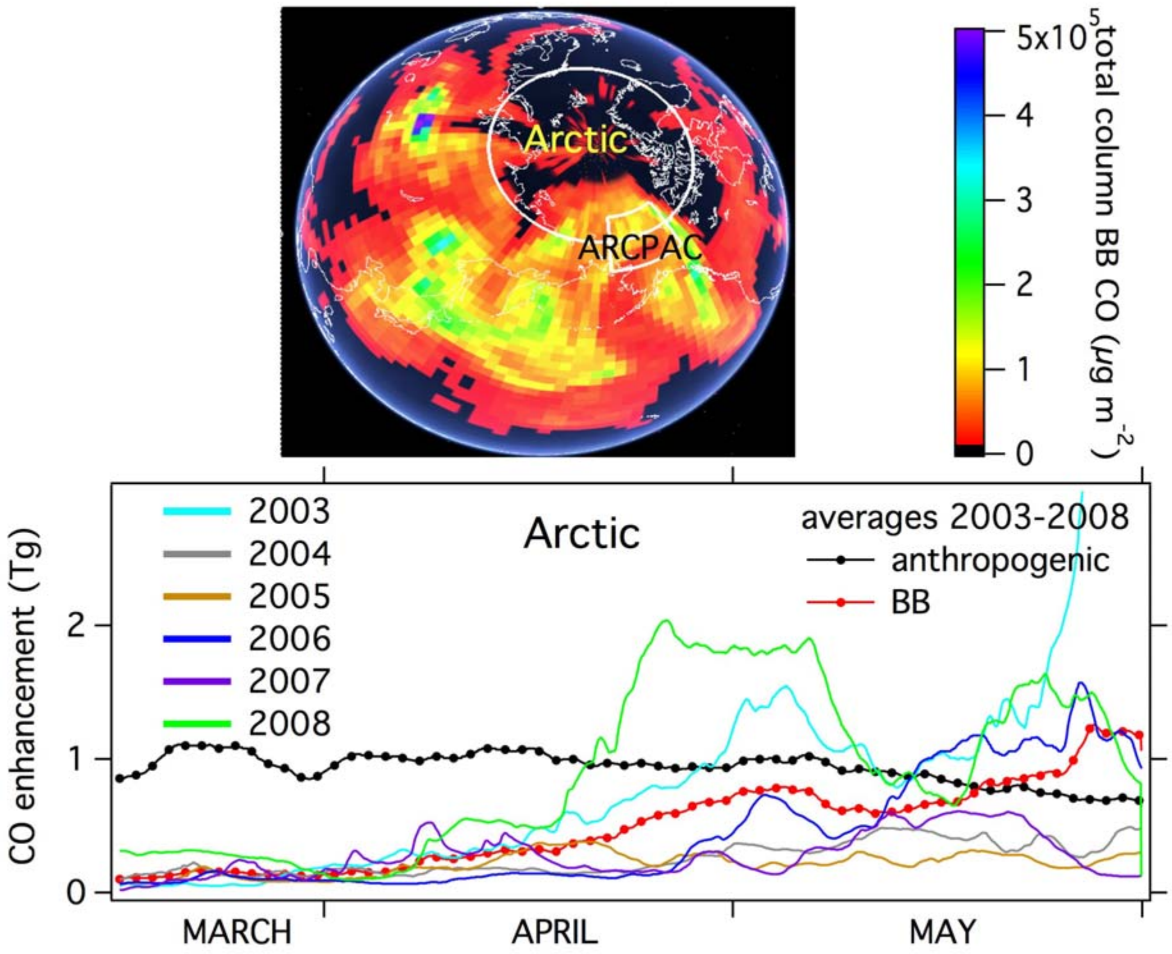


NASA



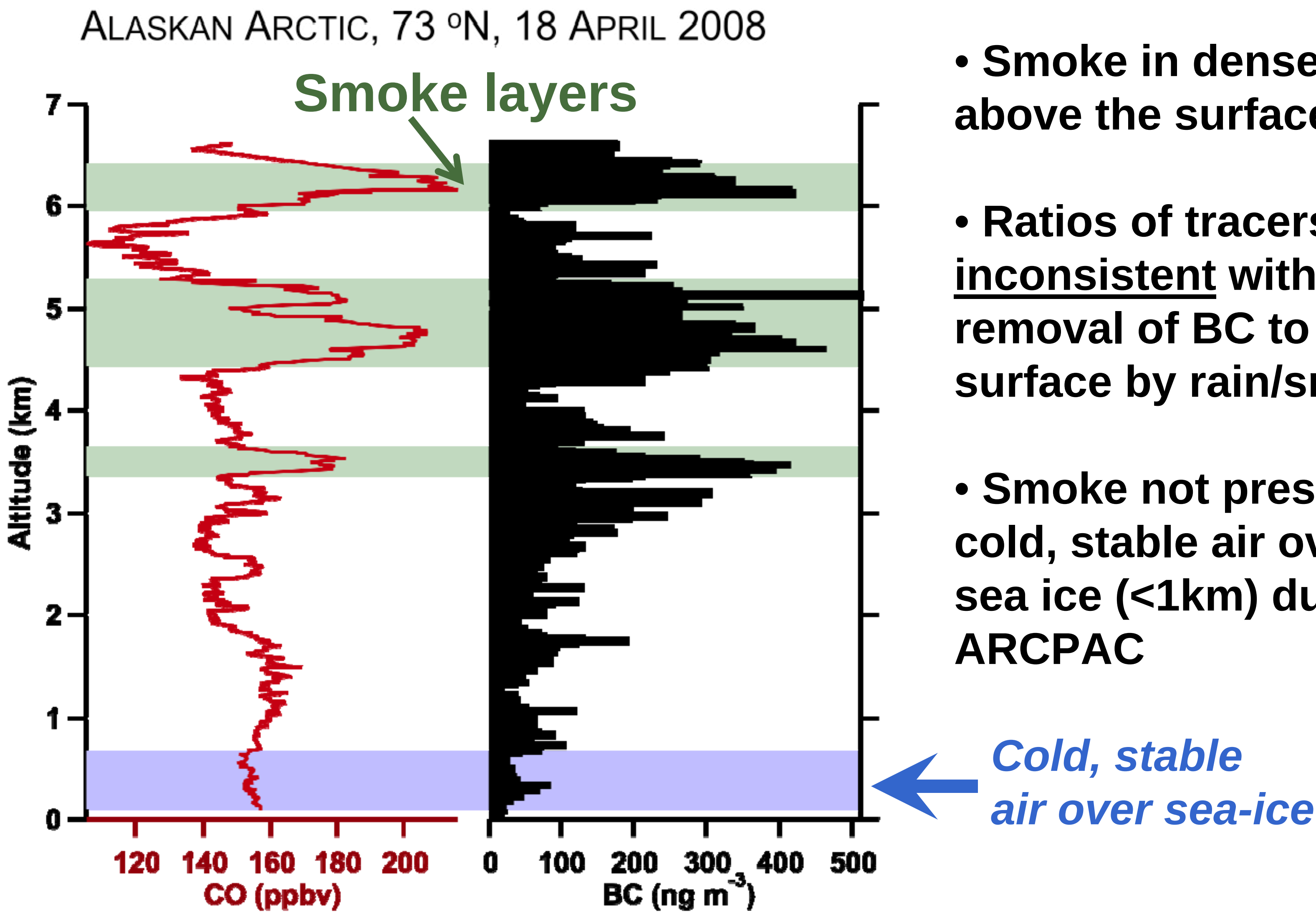
Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC)

ARCPAC: Biomass Burning Reaches the Arctic



- **Model simulates transport of smoke and pollution plumes to the Arctic, closely matching observations**
- **Transport of CO from fires is comparable to but more variable than from fossil fuel pollution in April and May.**
- **Smoke has much more BC than does pollution (per emitted CO)**

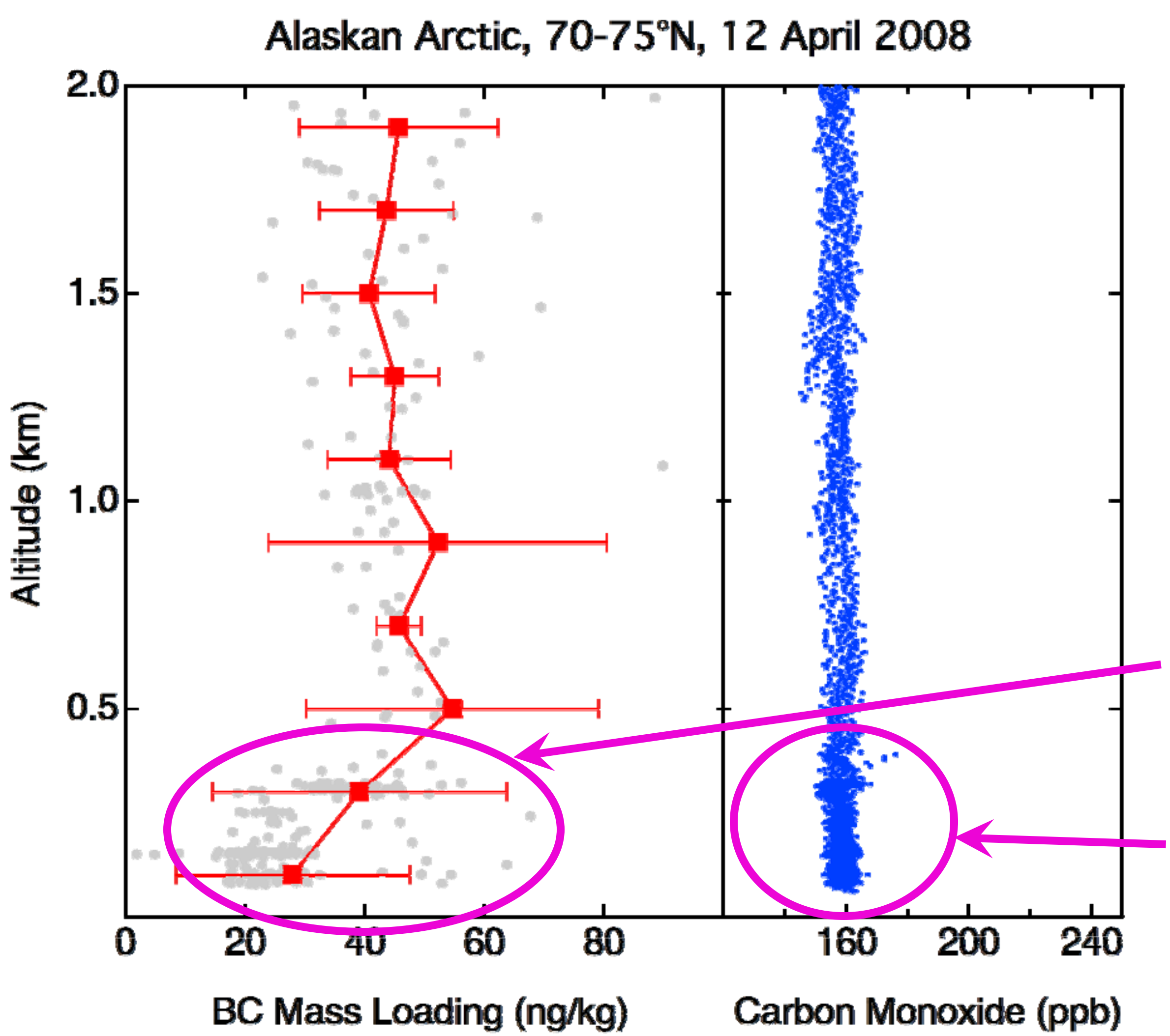
Does this smoke reach the snow surface?



- Smoke in dense layers above the surface
- Ratios of tracers are <u>inconsistent</u> with removal of BC to the surface by rain/snow
- Smoke not present in cold, stable air over the sea ice (<1km) during ARCPAC

Brock *et al.*, *Atmos. Chem. Phys.*, 2010

Deposition of BC to the snow



- **Profiles of BC mass and CO indicate BC aerosol is removed by deposition**
- **These data <u>do not</u> show biomass burning aerosol <u>aloft</u> depositing to the snow during ARCPAC**

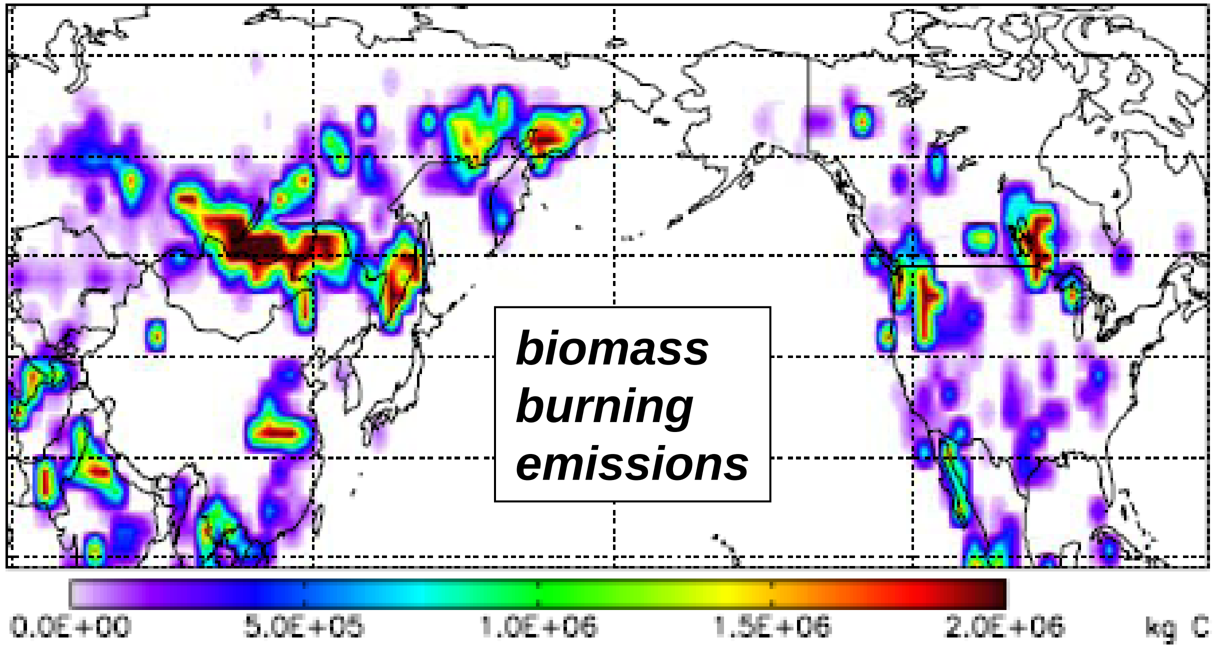
Less BC near sea-ice surface...

...but same CO as aloft

Spackman *et al.*, *Atmos. Chem. Phys.*, 2010

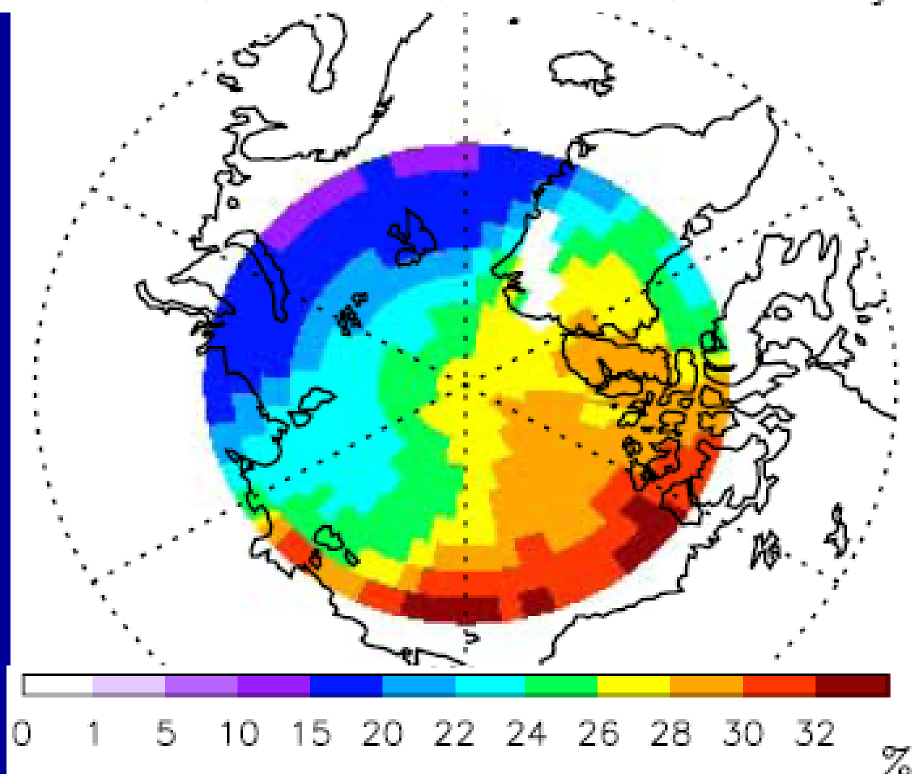
2003 Russian boreal fires

Generoso *et al.*,
***J. Geophys. Res.*, 112, 2007.**

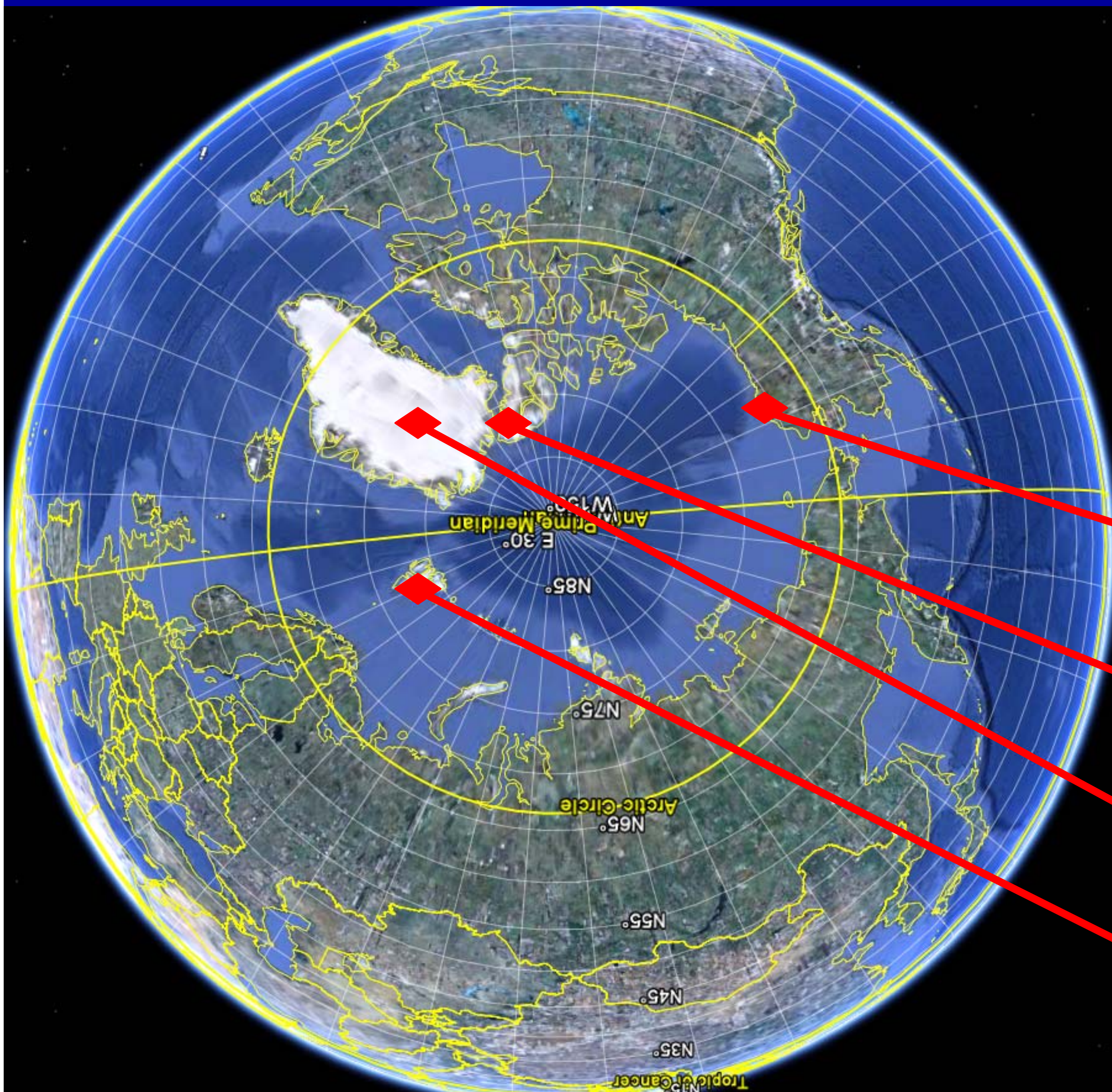


Russian boreal forest fires accounted for:

- 39% (May), 51% (June) and 56% (July) of BC deposition to Arctic ≥75°N
- 39% (May), 51% (June) and 56% (July) of BC deposition to Arctic ≥75°N
- 16% (May), 24% (June) and 33% (July) of atmospheric optical depth of aerosol



Contributions to air pollutants at: International Polar Year Spring field campaign in N. American side of Arctic



Hirdman *et al.*, *Atmos. Chem. Phys.*, 10, 2, 669, 2010.

Look at contributions to pollutants from 2000-2007 at:

Barrow, Alaska

Alert, Canada

Summit, Greenland

** 3208m asl*

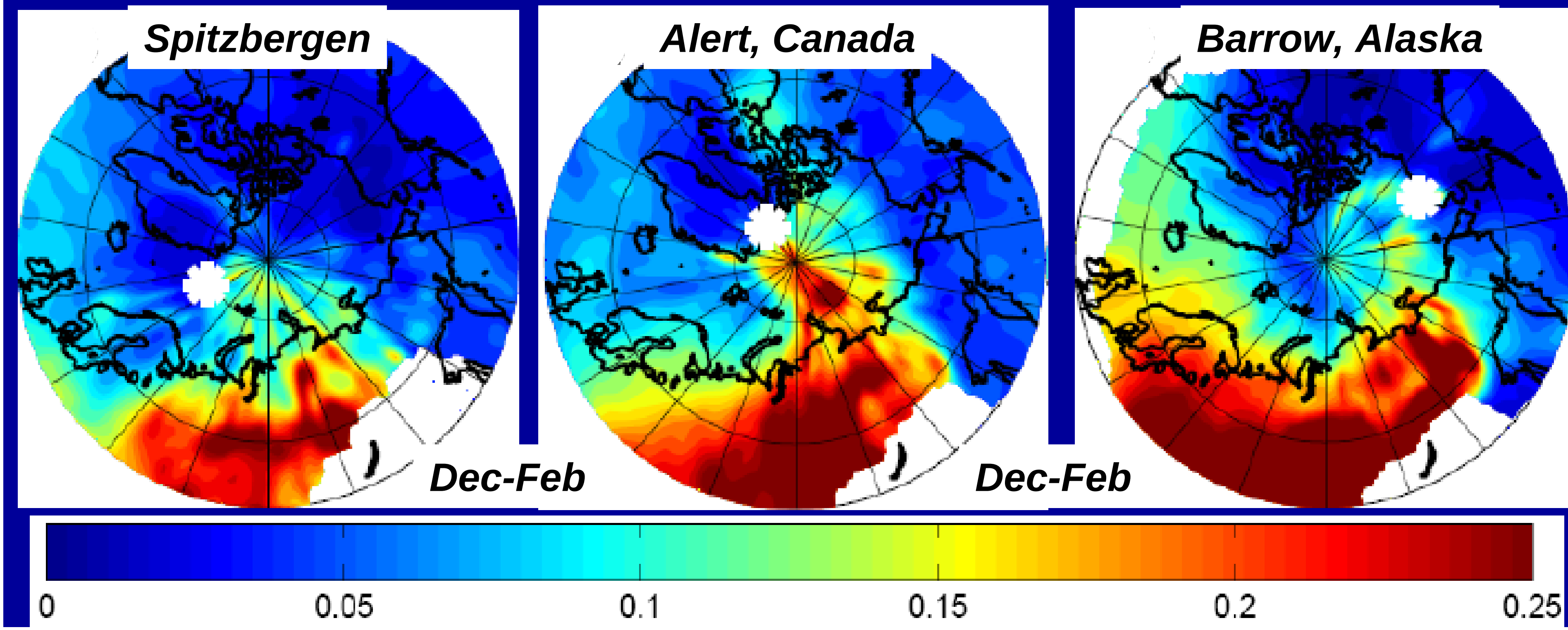
Spitzbergen, Norway

Contributions to air pollutants, N. American side of Arctic

Hirdman *et al.*, *Atmos. Chem. Phys.*, 10, 2, 669, 2010.

Look at source of black carbon for highest and lowest concentration events.

- During winter & spring (Dec-Feb & Mar-May):
  - High concentration events at Barrow, Alert & Spitzbergen are dominated by long range transport from Northern Eurasia
  - Low concentration events from source-free regions or from areas that experience strong precipitation scavenging such as the north Atlantic Ocean (Zeppelin, Alert) or Pacific Ocean (Barrow)

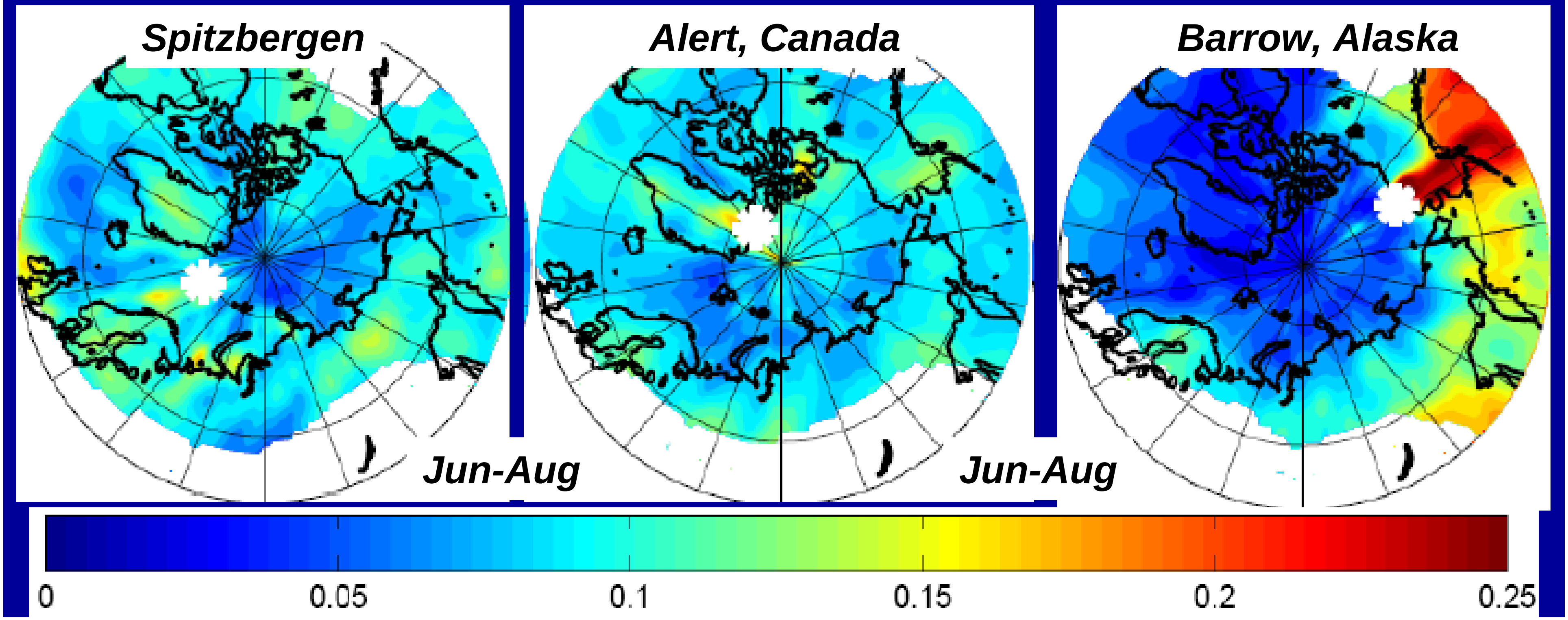


Contributions to air pollutants, N. American side of Arctic

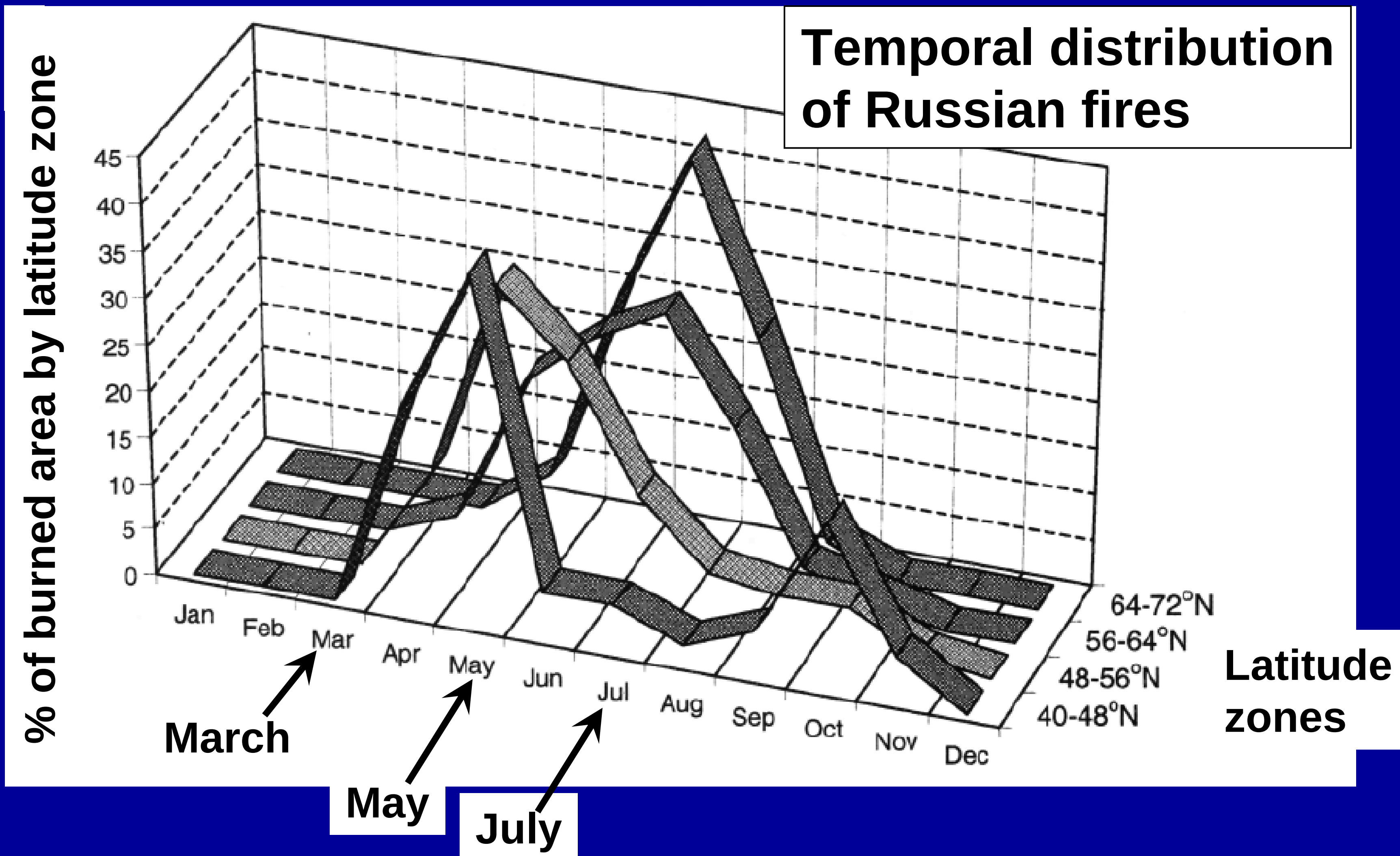
Hirdman *et al.*, *Atmos. Chem. Phys.*, 10, 2, 669, 2010.

Look at source of black carbon for highest and lowest concentration events.

- During summer:
  - Overall much lower concentrations
  - High concentration events associated with air descent from free troposphere (>2km altitude)
  - Zeppelin influenced by fires in northeastern Siberia; Alert and Barrow by N. American fires

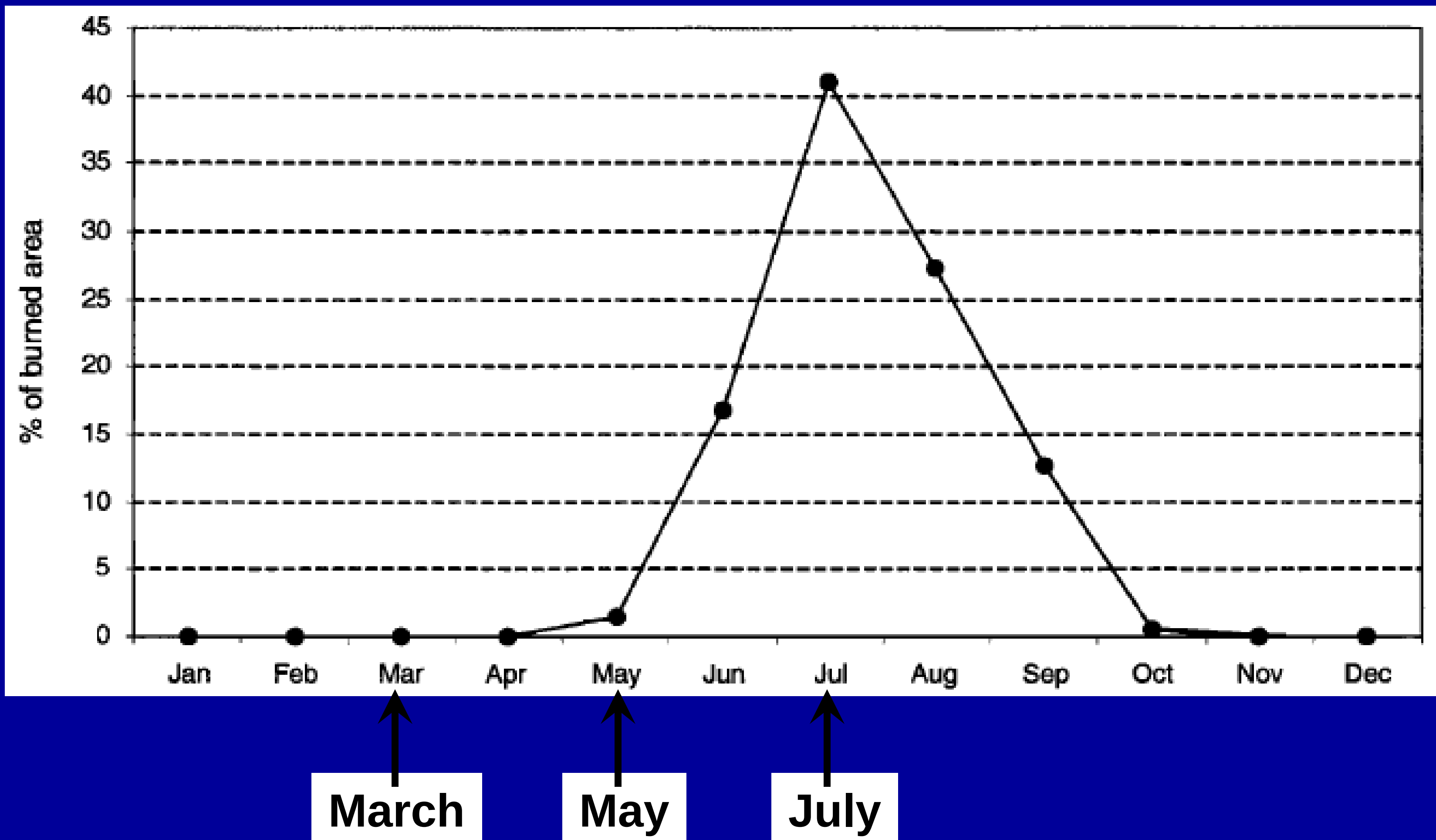


Why the dominance of emissions from Russian fires in the Arctic in Spring?

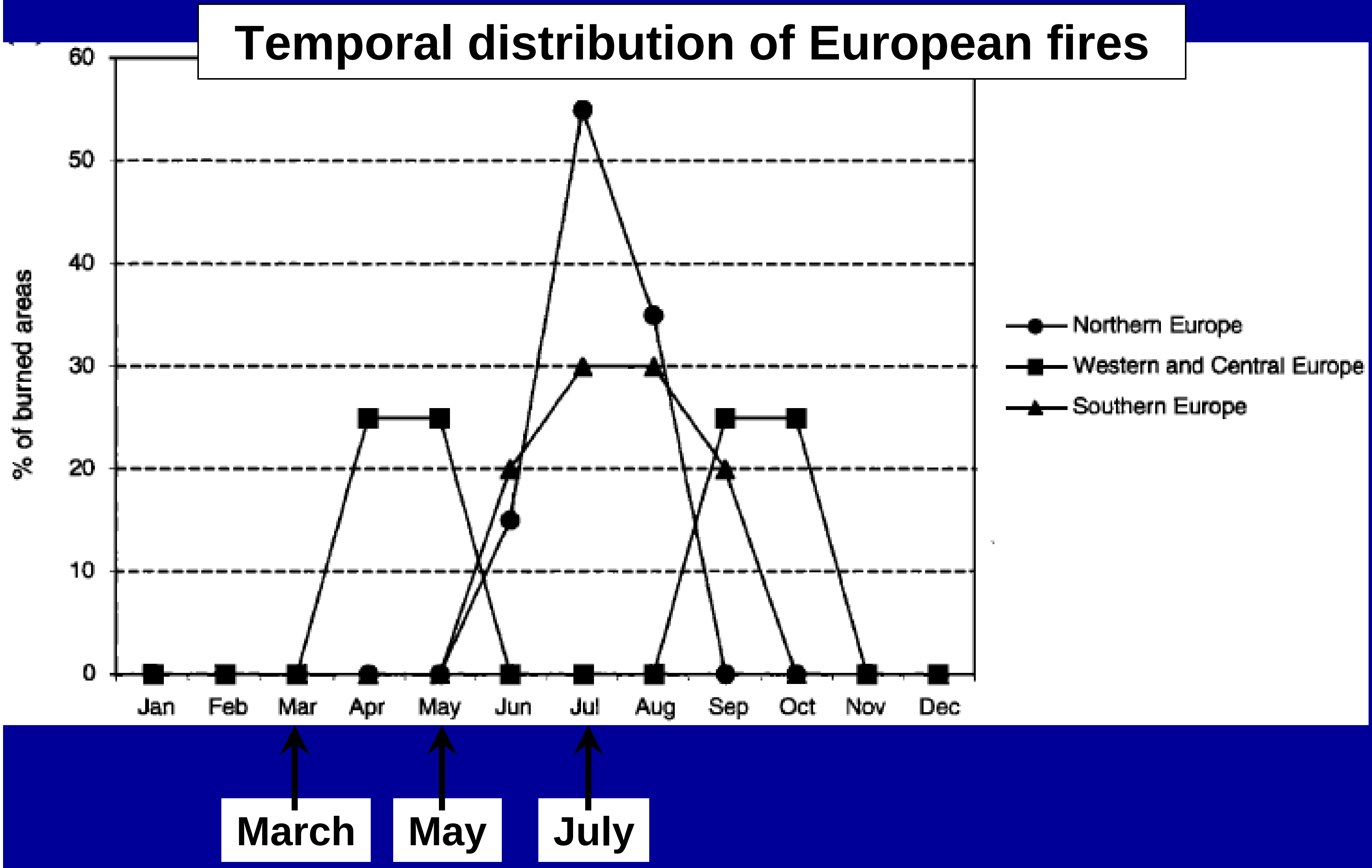


Why the dominance of emissions from Russian fires in the Arctic in Spring?

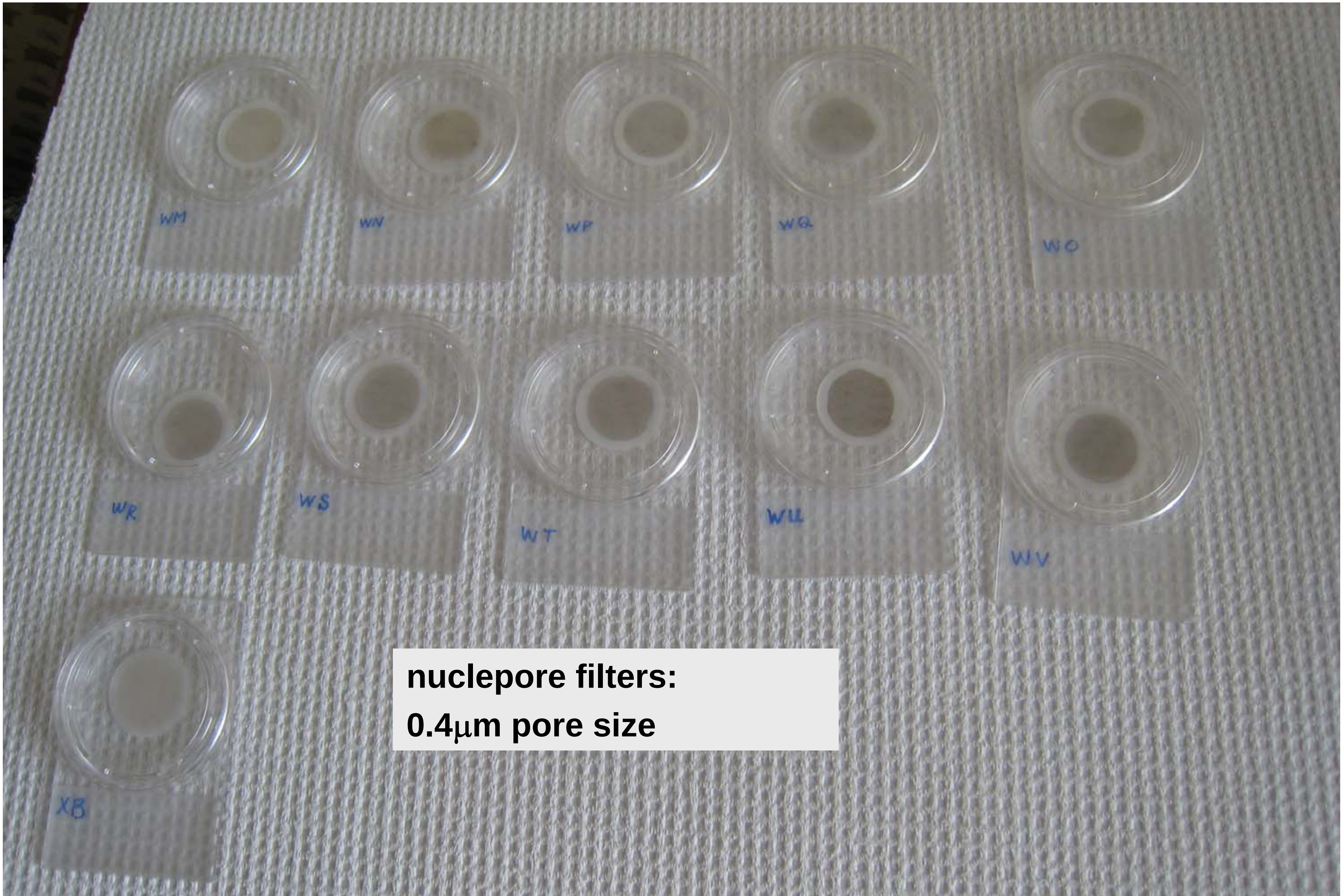
Temporal distribution of Alaskan fires



Why the dominance of emissions from Russian fires in the Arctic in Spring?

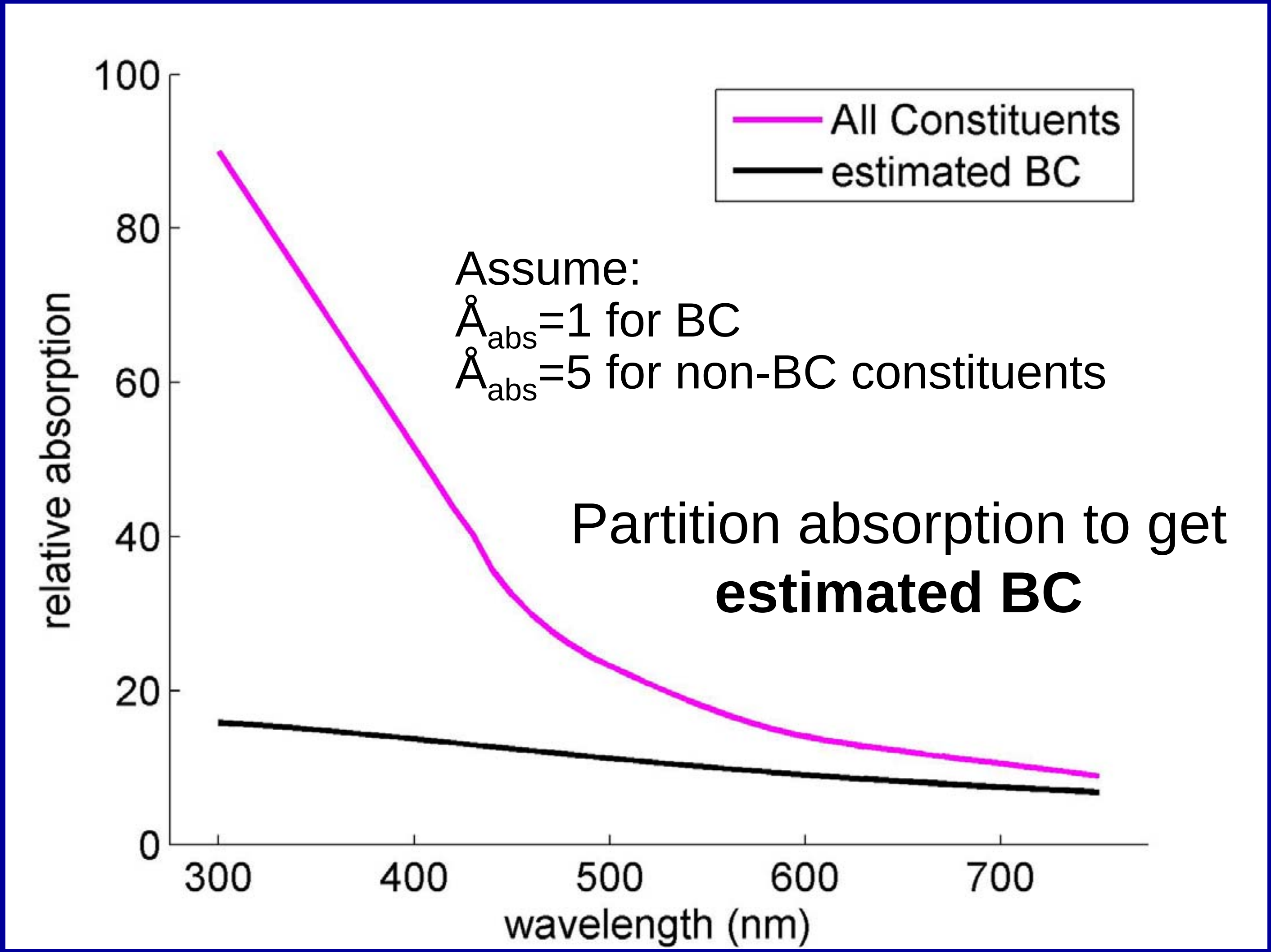


Field sampling of snow

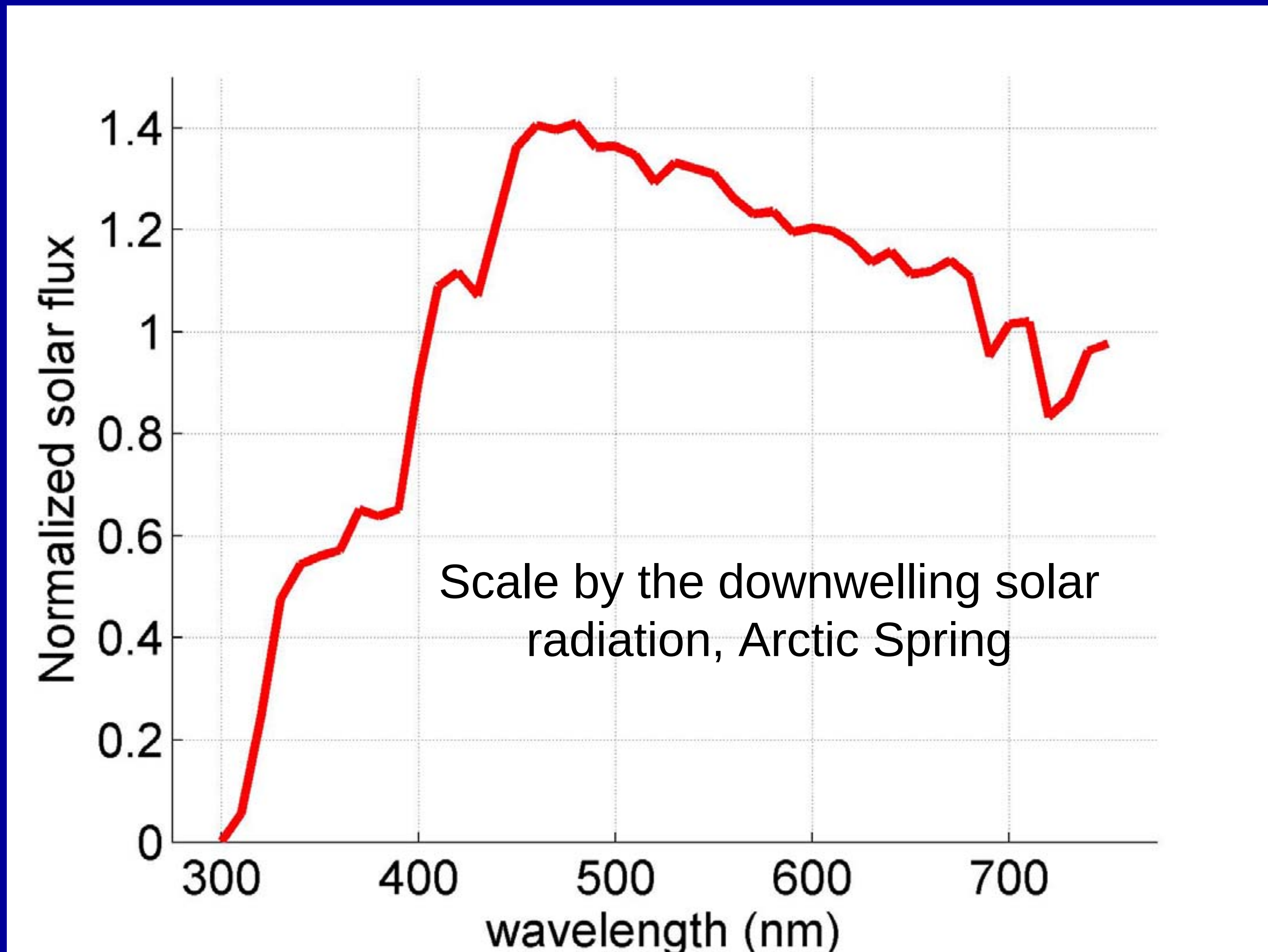


Filters from snow near Tiksi, Russia

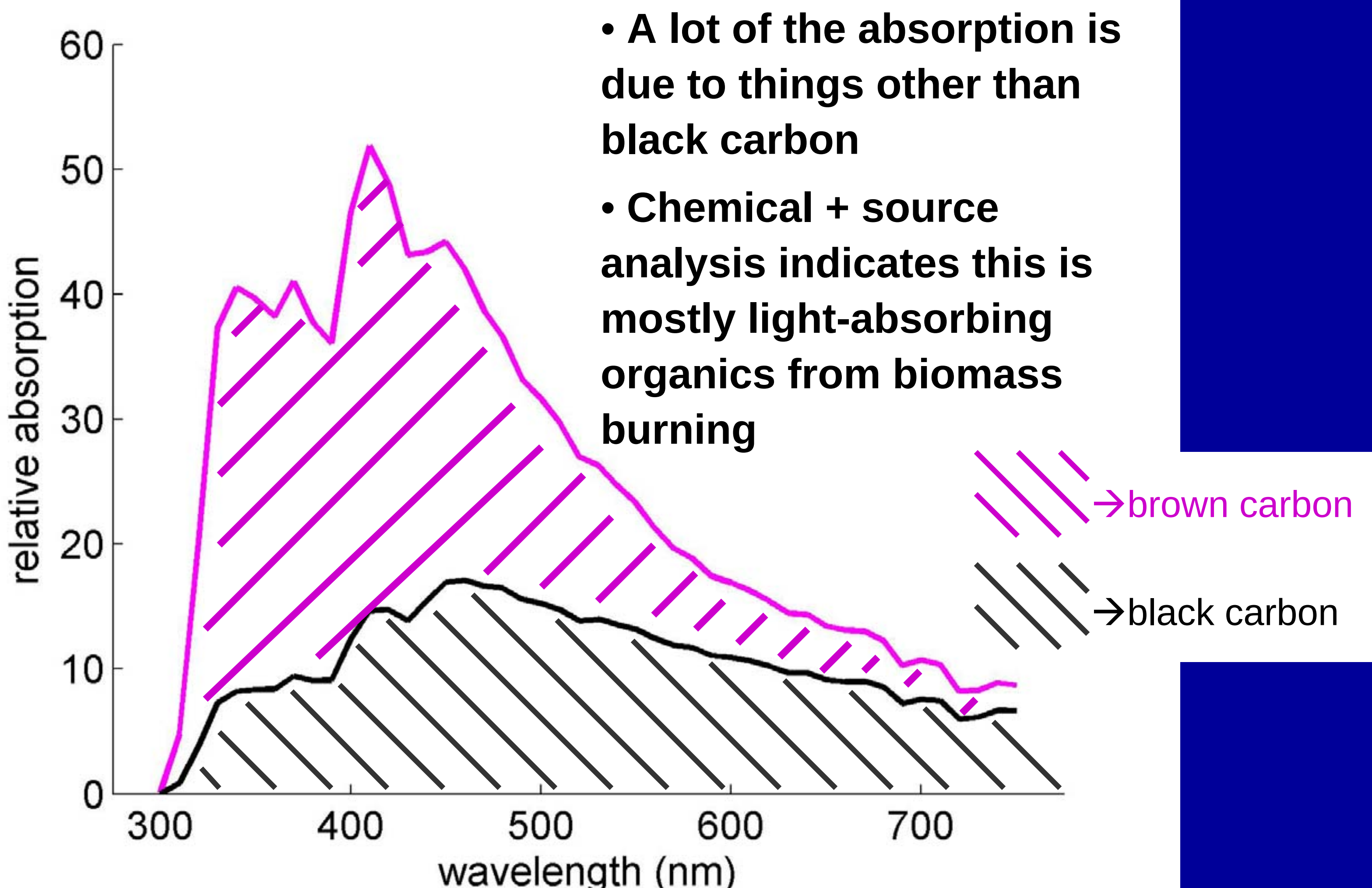
Wavelength dependence of absorption



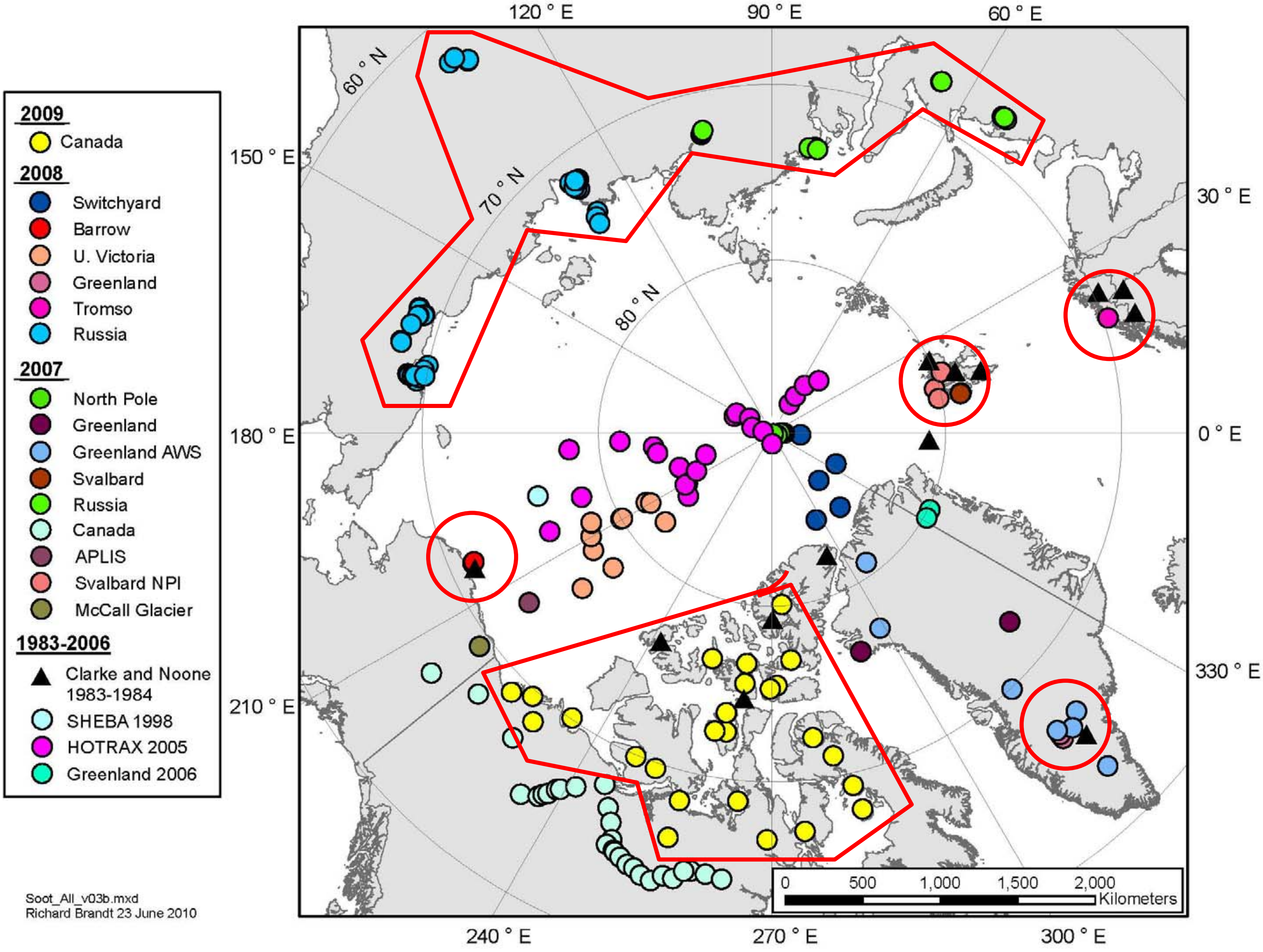
Wavelength dependence of absorption



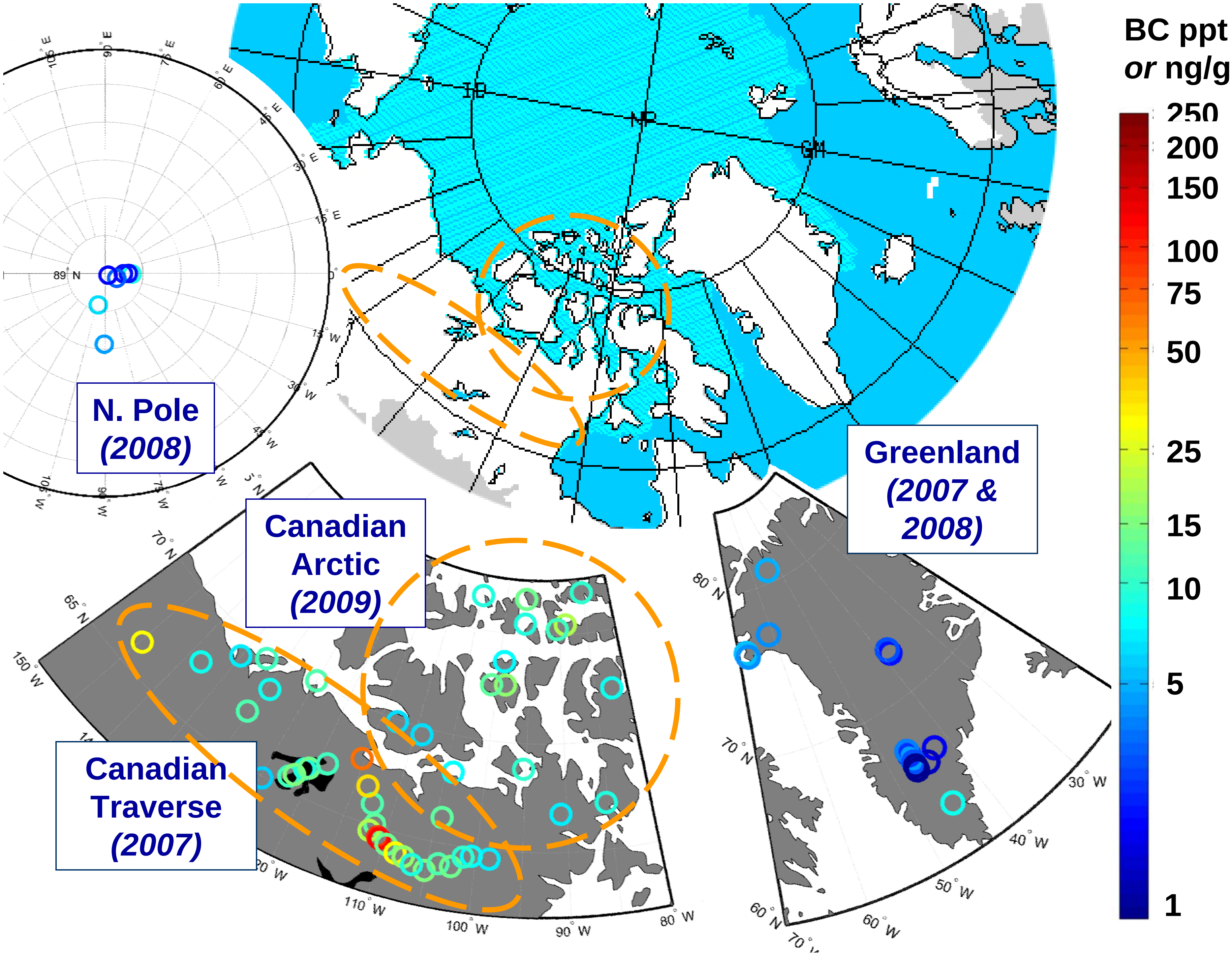
Wavelength dependence of absorption



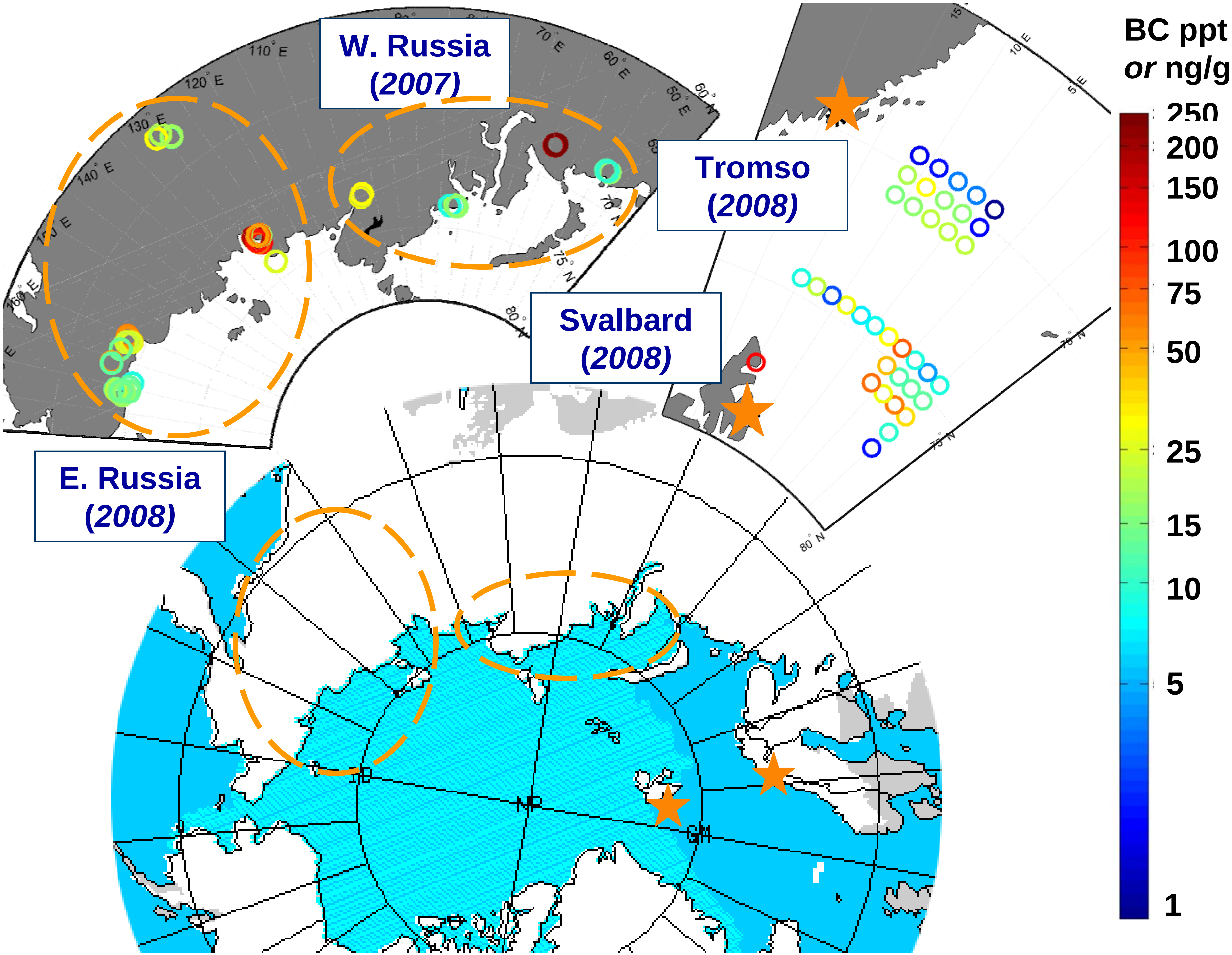
- **A lot of the absorption is due to things other than black carbon**
- **Chemical + source analysis indicates this is mostly light-absorbing organics from biomass burning**



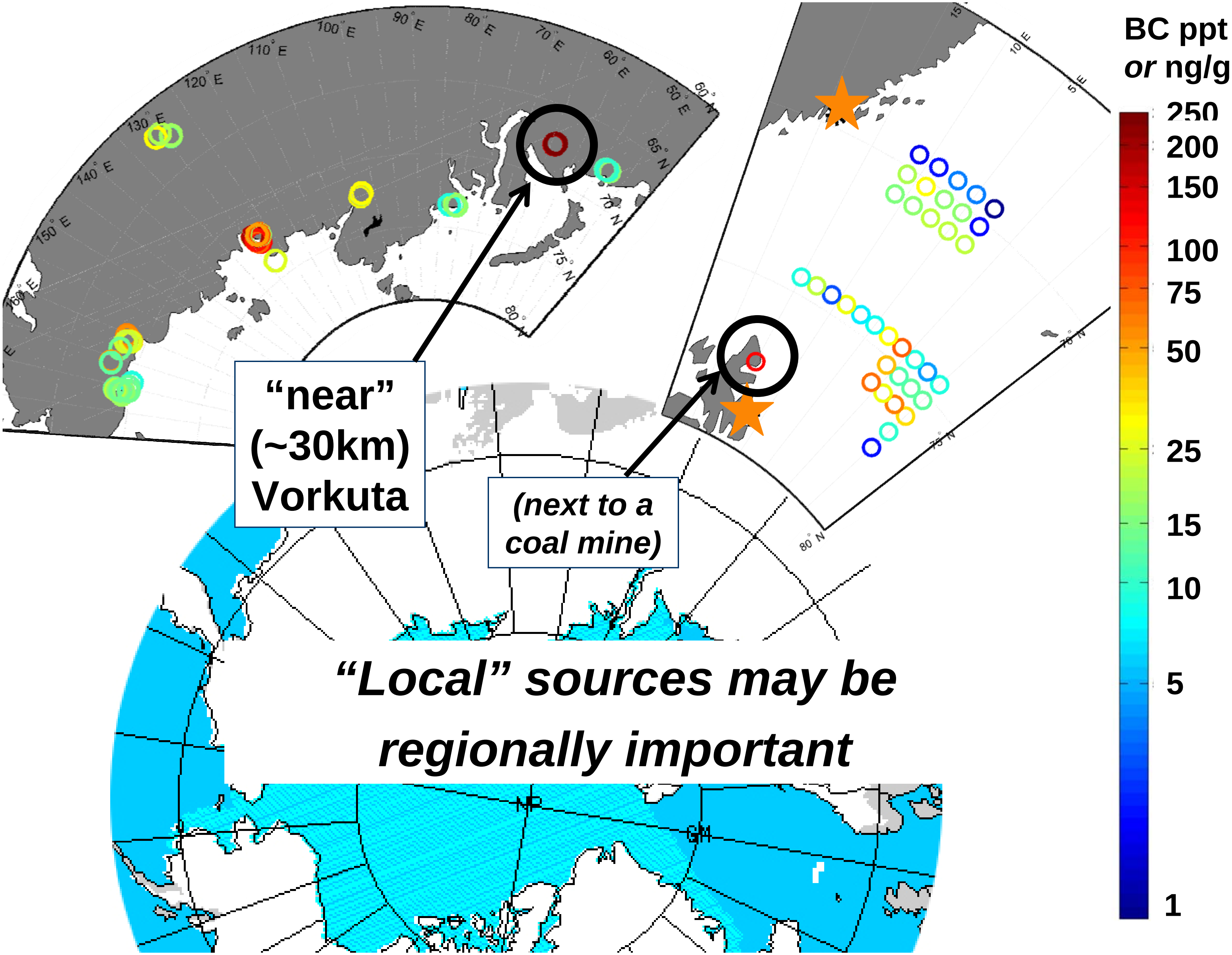
120 ° E
90 ° E
60 ° E
150 ° E
30 ° E
180 ° E
0 ° E
210 ° E
330 ° E
240 ° E
270 ° E
300 ° E
60 ° N
70 ° N
80 ° N
0 500 1,000 1,500 2,000 Kilometers
2009
Canada
2008
Switchyard
Barrow
U. Victoria
Greenland
Tromso
Russia
2007
North Pole
Greenland
Greenland AWS
Svalbard
Russia
Canada
APLIS
Svalbard NPI
McCall Glacier
1983-2006
Clarke and Noone 1983-1984
SHEBA 1998
HOTRAX 2005
Greenland 2006
Soot_All_v03b.mxd
Richard Brandt 23 June 2010



BC ppt
or ng/g
250
200
150
100
75
50
25
15
10
5
1
N. Pole
(2008)
Greenland
(2007 &
2008)
Canadian
Arctic
(2009)
Canadian
Traverse
(2007)
NP
GM



W. Russia
(2007)
Tromso
(2008)
Svalbard
(2008)
E. Russia
(2008)
BC ppt
or ng/g
250
200
150
100
75
50
25
15
10
5
1

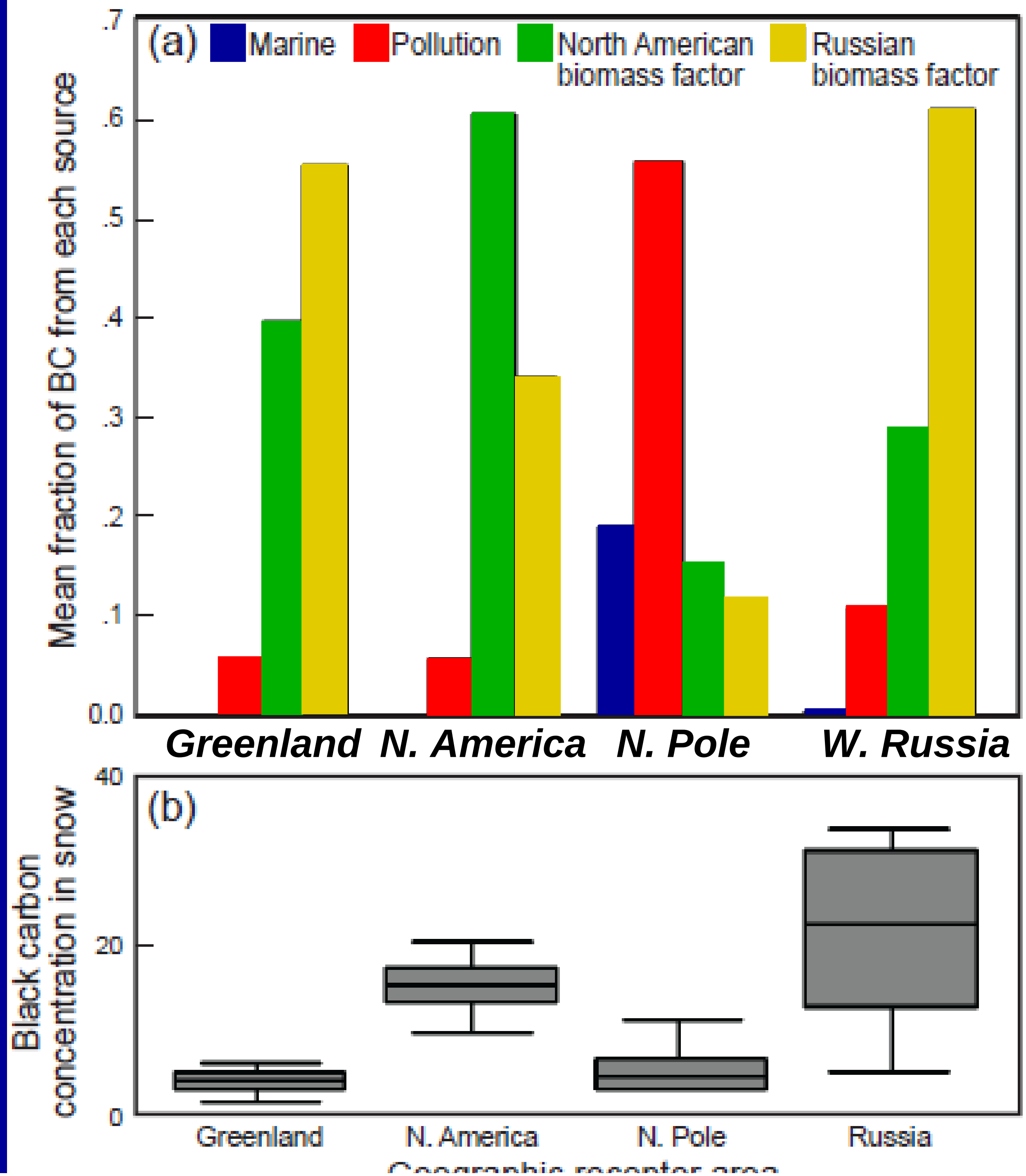

BC ppt
or ng/g
250
200
150
100
75
50
25
15
10
5
1
"near" (~30km) Vorkuta
(next to a coal mine)
"Local" sources may be regionally important
NP
GM

Chemical Analysis of trace species in snow (ions, organics, metals)

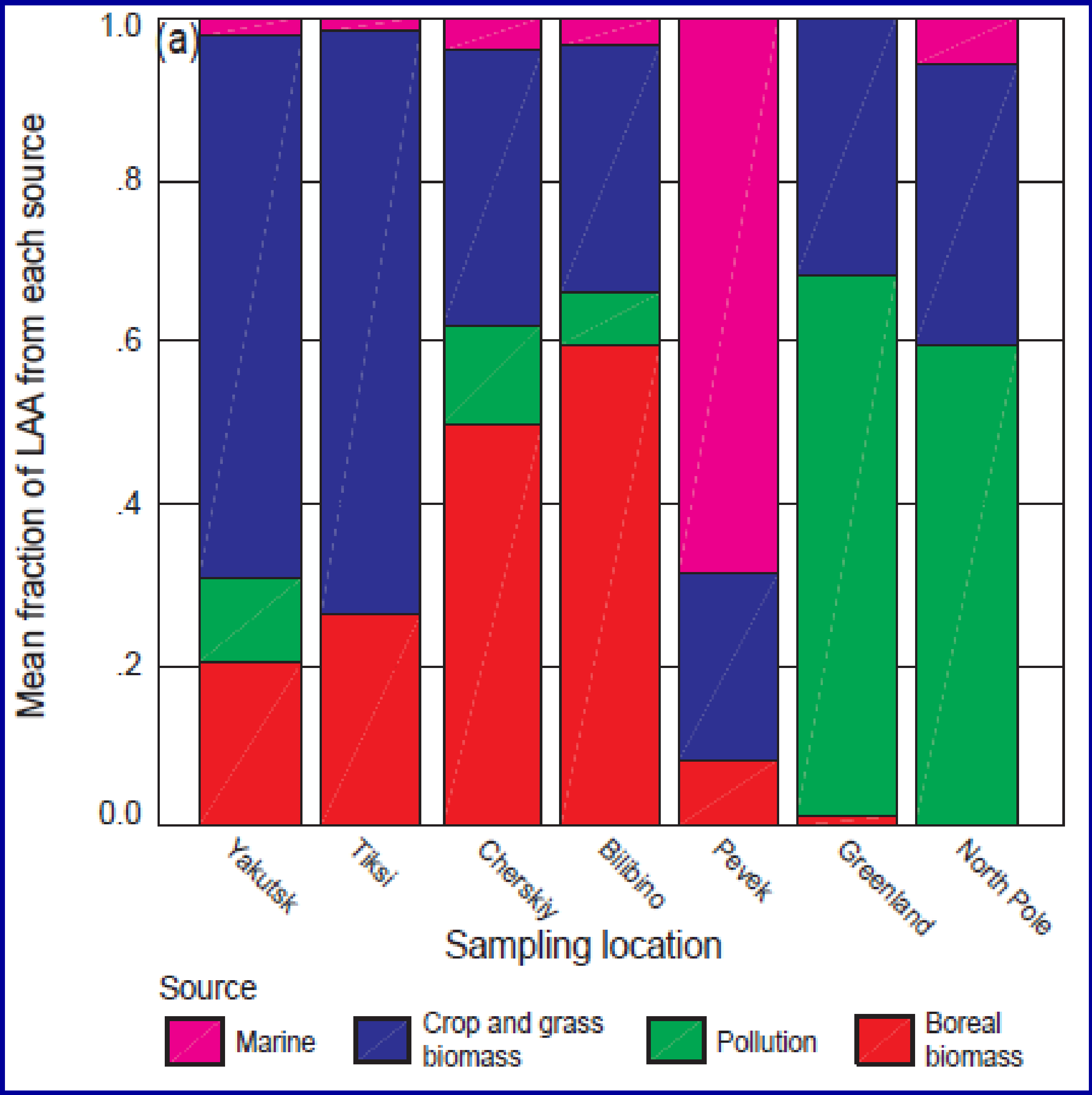
+ BC/nonBC Light Absorbing Aerosol equivalent concentrations

+ Positive Matrix Factorization

→ chemical “fingerprints” which describe most of the variability in BC



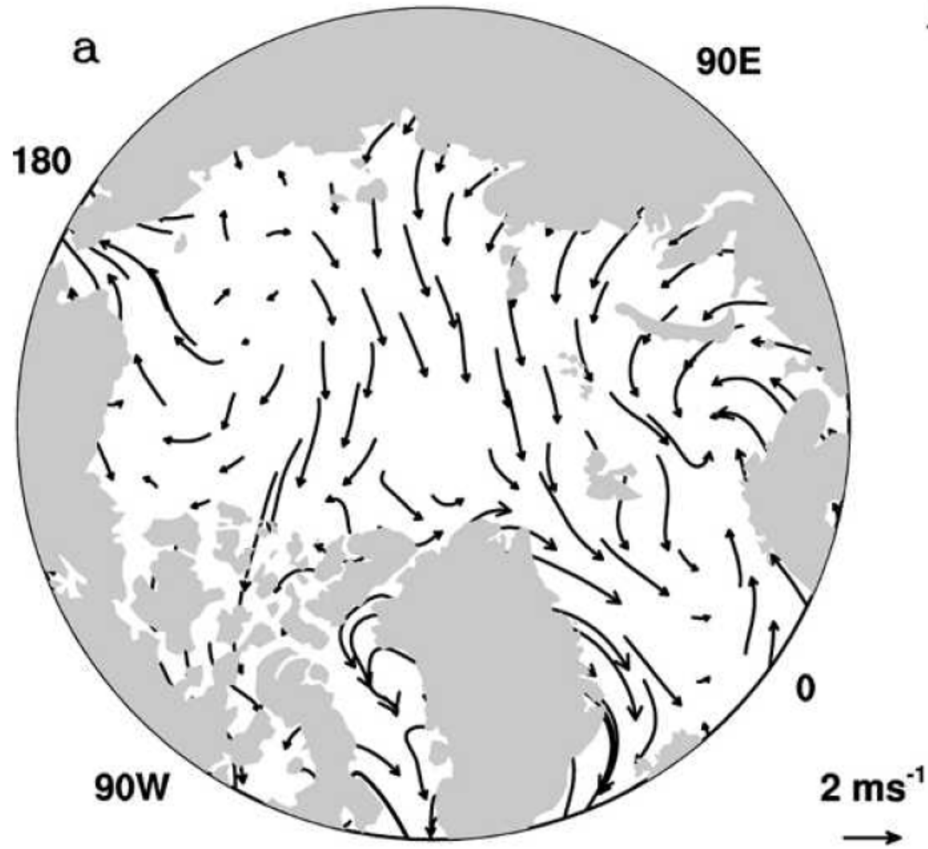
W. Russia



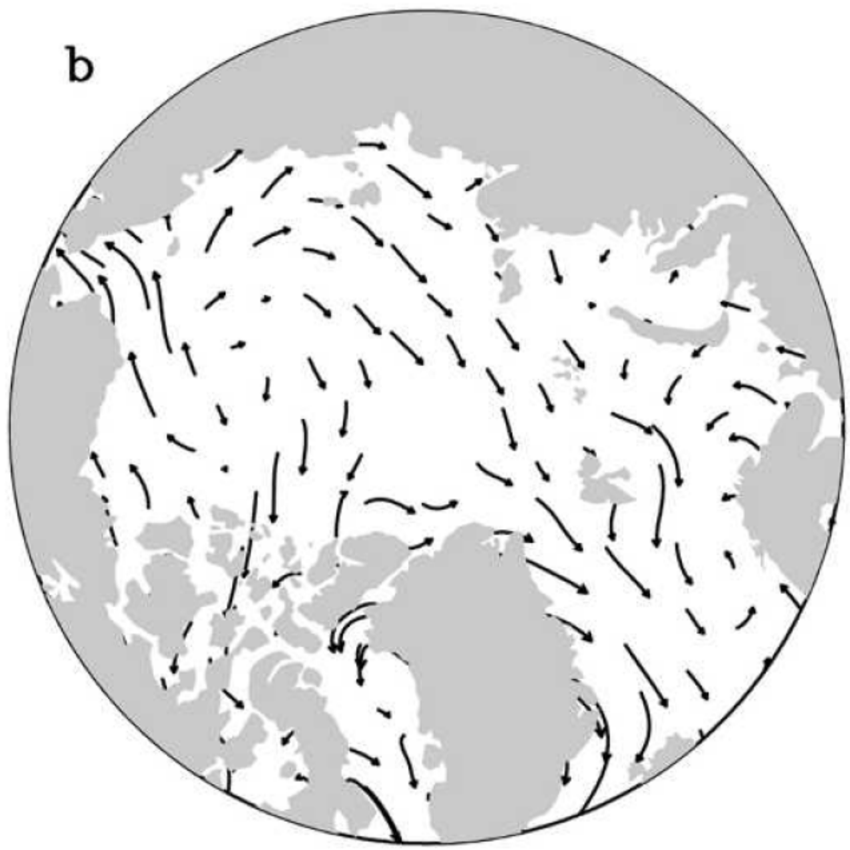
Greenland

EXTRA SLIDES FOLLOW

Average Arctic surface winds in winter & spring (1979-1999 average)



December-February

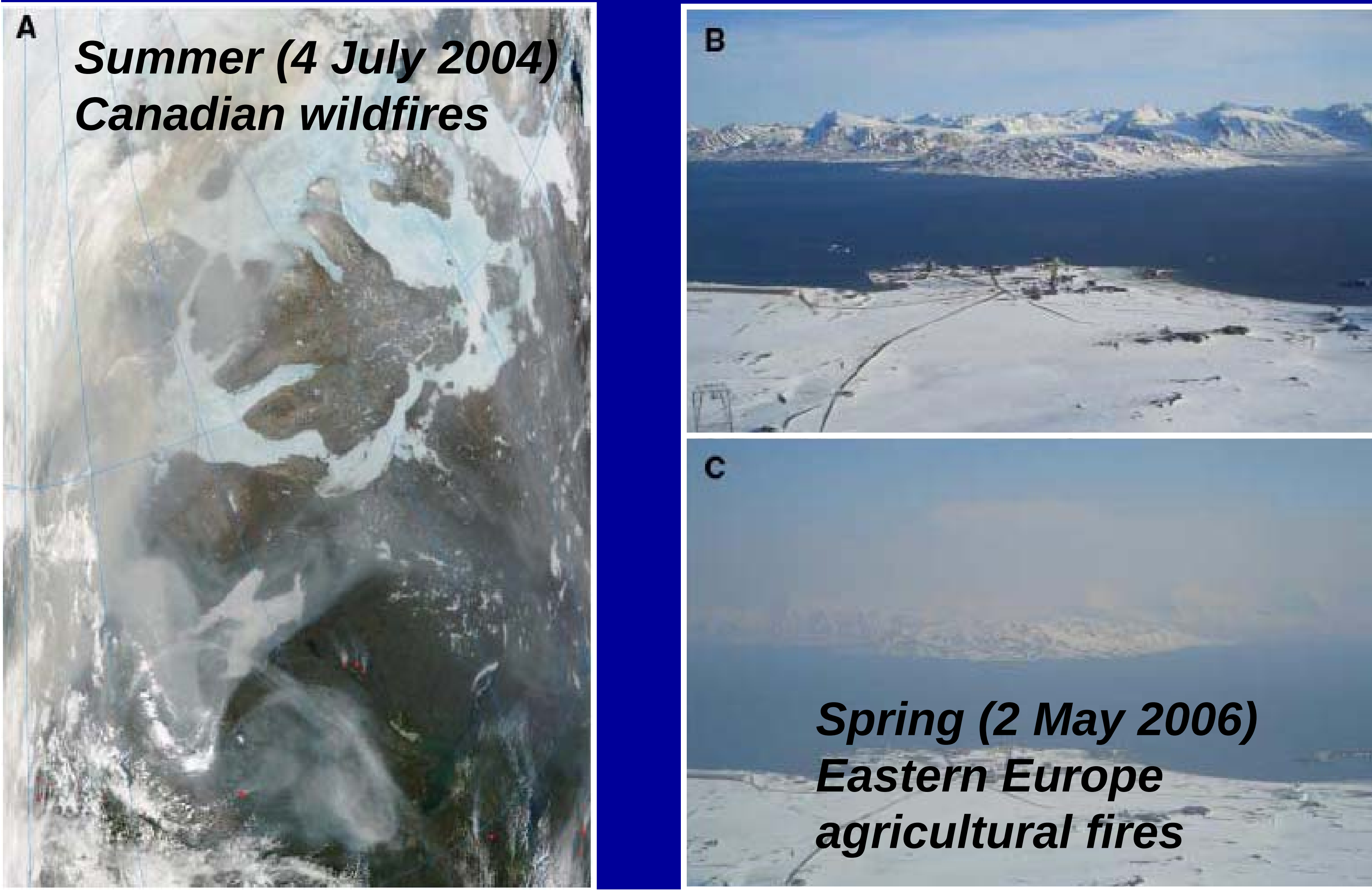


March-May

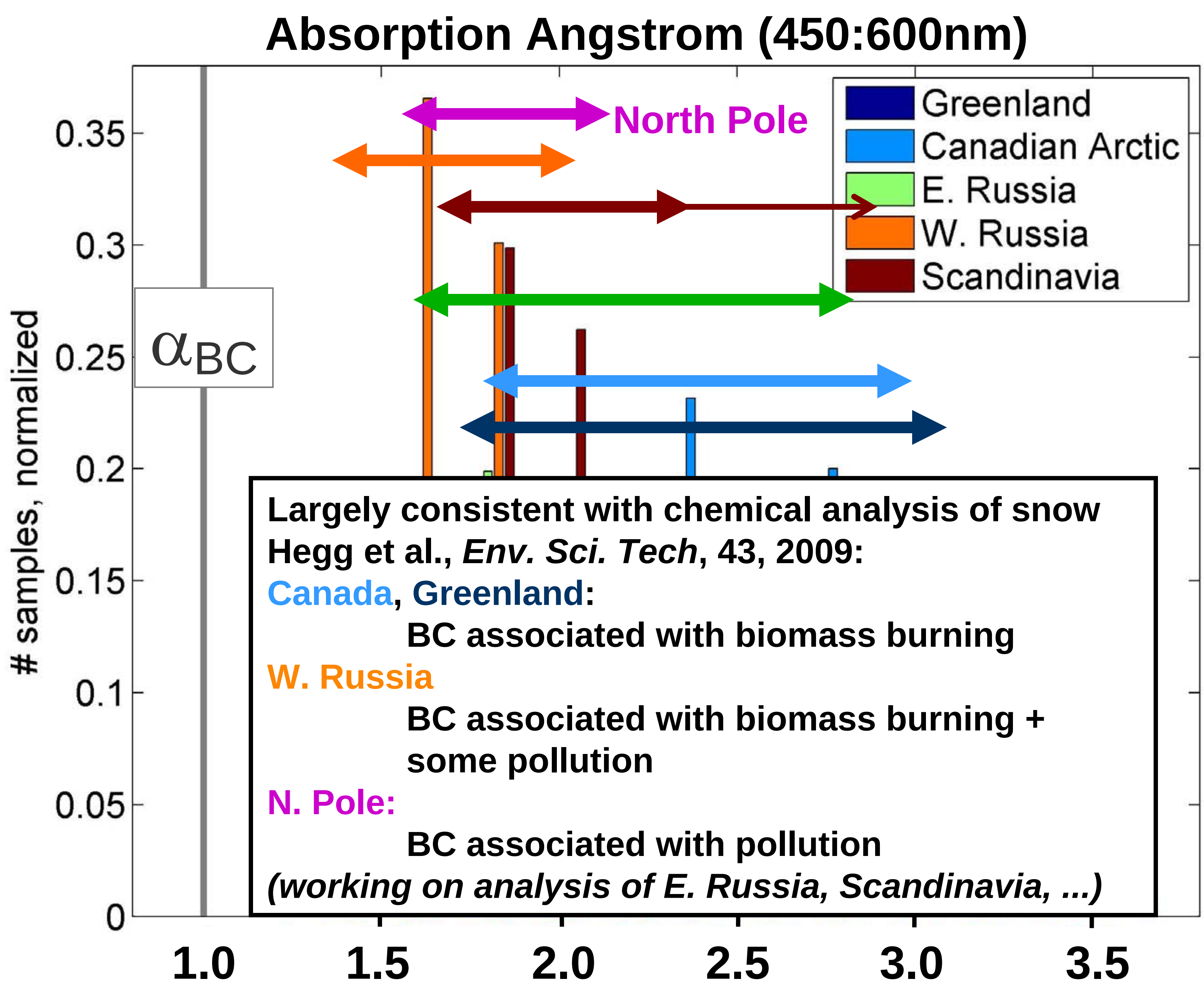
DeWeaver & Bitz, *J. Climate*, 19, 2415, 2006.

Observations of high-concentration events

Law & Stohl, *Science*, 315, 1537, 2007.



Snowmelt-filtering at Hydromet lab in Pevek (Chukotka)


Absorption Angstrom (450:600nm)
North Pole
Greenland
Canadian Arctic
E. Russia
W. Russia
Scandinavia
α_{BC}
samples, normalized
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
1.0
1.5
2.0
2.5
3.0
3.5
Largely consistent with chemical analysis of snow
Hegg et al., *Env. Sci. Tech*, 43, 2009:
Canada, Greenland:
BC associated with biomass burning
W. Russia
BC associated with biomass burning + some pollution
N. Pole:
BC associated with pollution
(working on analysis of E. Russia, Scandinavia, ...)

Key message: *Accurate representation of all light absorbing aerosol in snow*

combustion "brown" organic carbon,
soil organic carbon, mineral dust, algae

- *~25-45% of light absorption by aerosols in Arctic snow is due to non-BC constituents*
- *If this is co-emitted with BC it will go away if mitigate BC sources → more bang for the buck!*
- *If it is not co-emitted with BC (e.g. mineral dust, algae) mitigation of BC source will have less effect than expected*

Chemical + PMF analysis → source types